

Synchrotron Radiation Detector Roadmap Meeting Notes

Version 2.2

R J Cernik and G E Derbyshire

Introduction

Version 2.0 of the detector development roadmap builds on the previous document (version 1.6) with the addition of a number of new projects and the consolidation of others. This updated information was obtained from a meeting held in Chester on the 8th & 9th March 2004. An international audience of detector developers, facility providers and users met to discuss developments, trends and priorities in SR detector development. The meeting addressed only the X-ray developments on the advice of the SRS scientific advisory committee. Lower energy detectors and applications will be considered at a separate meeting. The medium to long-term aspirations of the synchrotron detector programme are largely unchanged. Some technologies have developed considerably in the two years since the last meeting, these were identified and dovetailed with the roadmap. As with the previous report the short and medium term developments concentrate on what is available to the UK communities now. It is clear that some projects on the short-term list have only recently been funded, some of the longer-term developments may still require international collaboration with SR sources such as the SLS. Presentations from Brookhaven and from the SLS showed possibilities for scientific co-operation. There was a clear recommendation for the establishment of a detector materials development programme specifically associated with high-energy X-ray applications. ESA has made significant progress in the development of CZT; TlBr, GaAs; InP; and HgI₂¹ for detector applications. Wherever possible the report again aims to extract the developments that are likely to have a major impact and develop synergies between research areas. The strategy is a synthesis of international and national developments focused on the UK needs, especially for the SRS and DIAMOND. The X-ray detector development programme associated with 4GLS will be addressed elsewhere. Table 1 below shows a list of the main detector development that would benefit the SR community the most based on scientific impact and to a lesser extent community size.

Table 1 SR Detector Summary (see glossary for anonyms)

Science Area	Short Term (1-2 years)	Medium Term (2-4 years)	Longer Term (5years plus)
Spectroscopy	Buy Commercial XAFS STRIP detectors IMPRESS ERD Silicon drift detectors	Hybrid Pixel Detector High energy, high Z materials IMPRESS	Hybrid Pixel detectors APS Cryogenic Detectors
Diffraction	HOTWAXS, GMSD2D DIFFEX	Multiple DIFFEX APS Flexible TFT devices	3D detectors APS
Imaging	Amorphous Silicon	APS	Large array APS

¹ All references : Nucl.Instr.Meth A unless otherwise stated : CZT, Vol 484 , p 242 (2002), TlBr, Vol 509, p 47 (2003), Vol. 497, p 370 (2003), Vol. 497, p 359 (2003), GaAs, Vol. 484, p242 (2002), IEEE TransNuclSci NS 49, p 2513 (2002) and NS-50, p 723 (2003), InP, Vol. 487, p 435 (2002), HgI₂, Vol. 479, p 535 (2002)

Questions addressed by the meeting

The following questions were circulated and discussed by the various breakout groups in spectroscopy, XRD and imaging. The summaries of the breakout sessions follow.

- Have we missed any technologies in our survey?
- i.e. what should be present in the roadmap?
- Are any of our existing technologies redundant?
- Should any of the detectors described in the document be replaced?
- Are the short, medium and long term goals reasonable and achievable?
- What should we do about software development?
- Are there any technologies that can now be bought?
- i.e. is there anything we should drop?
- Are our assumptions in the roadmap document still valid?
- What are other groups achieving in similar fields elsewhere in the world?

More generally

- Are your current experiments being limited by detectors? If so in what way?
- What are the trends in your area of science that will impact on detector performance?
- near future
- longer term
- Is there a radical approach that could be introduced if there were no detector limitations?
- Does the roadmap adequately cover your area of science?
- If yes be specific (where is it good, where not so good etc...)
- If no be specific and say in which way it should be covered from a detector point of view.

Spectroscopy

• XAS detectors - short term

Compact Germanium detectors are now an accepted way forward and the compact monolithic design is beginning to deliver detectors that can, with appropriate readout electronics, handle the flux concentration from focussing optics. The requirement in this area is for detectors that work at high rate with a reasonable number of channels

There is an immediate proposal to upgrade station 9.3 with compact Germanium detector and with XSPRESS2. XSPRESS2 will use higher rate ADCs and new FPGA technology. Estimates for a 16 channel C-TRAIN and a new XSPRESS system. XSPRESS may be best approached with a joint proposal with the Nuclear Physics community (IMPRESS) that will use similar approach to XSPRESS

Hardware £200k effort 0.5 to 1.0 Staff years. Can be achieved in 12 months (or less)

This upgrade (in partnership with industry) would work to reduce the cost per system by using CLRC intellectual property to offset costs of detectors bought from ORTEC through technology transfer.

XMCD Gas microstrip detectors can be used for X-ray Magnetic Circular dichroism and soft X-ray. This project would be achievable in less than 18 months with already proven technology.

• XAS detectors - medium term.

A highly pixelated compact detector based on output from the IMPACT programme funded by Technology Foresight programme has proven this technology. The development of these detectors will be concentrated in the 10keV to 200keV.

These detectors would have to operate at room temperature and have sufficient throughput rate to be used as very close to sample detectors. Option would include detectors that could be easily moved around with the fluorescence radiation close to a sample. For example, to avoid diffraction peaks, or to be quickly moved away from the sample area when a diffraction pattern is required. The hybrid pixelated detector approach allows for the detection medium to be Si, GaAs or CZT depending on the energy range that is required.

The project will be costed in a similar way to SHAMROC to give greater detector flexibility. The readout system will be developed for ease of use.

- **XAS detectors - longer Term**

More compact readout with three side butting to allow tiling would be the next step. The readout chips would need significant redesign potentially with ADCs on chip. This development would make use of the already funded PPARC work in this area in compact hybrid detectors

Science drivers for higher spectral resolution detectors that are capable of measuring edge shifts in fluorescence energy are now being addressed by new detectors that will have sub 10 eV resolution. These detectors are available in a low channel number configuration using either Transition Edge Sensors or Superconducting Quantum Tunnel Junctions. The United States SR biological spectroscopy community are actively pursuing these detectors with transfers of technology from Space applications. Within the UK a similar opportunity exists. This is being pursued under the Basic Technology Funding proposal however if this is not successful another way of funding needs to be found. Not only must the detectors be made to have a higher throughput, probably by developing higher number of pixels per detector but also the cryogenic electronics and the interface electronics to a normal temperature environment.

Diffraction

- **Diffraction - short term**

Many scattering detectors are based on the RAPID interpolation system. The detector itself is based on a microgap wire detector. The ease of manufacture could be improved by replacing the wire planes with microstrips. Gas microstrips will also be necessary where high-count rate and medium angular resolution are required. Gas microstrips and solid-state strip detectors will naturally replace wire detectors in the future and a high level of support should be given to facilitate these developments through specific short-term development proposals. Thus far RAL is the centre of excellence in this technology and this resource should be fully utilised. However the RAPID system is likely to remain competitive for a considerable time into the future in the niche field of SAXS WAXS. For this reason CCLRC should collect together the various improvements and upgrades to the RAPID1-RAPID2 systems and fund them centrally.

The DIFFEX Prototype is a photon counting detector based on a silicon strip design. As a concept DIFFEX carries on from the preliminary work carried out at Daresbury with University of Glasgow and the output of the IMPACT programme. The parts for DIFFEX were developed by CCLRC through internal funding but now need specific funding to be engineered for use on an SR diffraction station. Longer term the development of DIFFEX will be combined with the development of 3-dimensional semiconductor detectors that will allow the detection of higher energy X-rays with high efficiency and excellent spatial resolution. DIFFEX detector electronics could be combined with HOTWAXS (High Overall Throughput Technology Wide Angle X-ray Scattering) to give a compact detector electronics system.

Specifically designed fast scintillation detectors to receive the output from multiple analyser assemblies will be necessary. This is a short-term project requiring very little development.

- **Diffraction - medium term**

A large angle coverage detector for Diffraction could be built which covers 120° . This would comprise several DIFFEX tiles that would need redesign in order to minimise dead area between tiles. We may collaborate with the Swiss light source in this area.

A detector based on bump bonding with 1.5 dimension would be very useful for obtaining more information about the homogeneity of the diffraction pattern. This could be developed from the basic building blocks for a 2 dimensional detector that would follow in the longer term.

All these activities track the development of new materials such as CZT, GaAs, or HgI for high-energy work. Additional support will be needed to utilise the latest materials in out applications. This would be required for SRS and Diamond.

- **Diffraction - long term**

Longer term would require development of area detectors similar to IMPACT. Hybrid pixellated detectors with 100μ

Imaging

Detectors for Synchrotron X-ray Imaging

The group discussed the current and future demands on synchrotron x-ray detectors from imaging science. We included a review of the wants from plasma diagnostics since this science may benefit from detector developments in our area.

Current status

The choice of detectors available on SR sources is generally amongst commercial off the shelf (COTS) systems. There are notable exceptions, for instance the Frelon camera at the ESRF (ID19).

Current demands

Experiment	Image area	Image resolution	Exposure time	Time between images	Energy resolution
Medical 2-D radiography	> 100 mm by 100 mm	< 10 micron FWHM	< 1 second	< 10 Seconds	Useful for dichromography
Medical CT	> 100 mm by 100 mm	< 10 micron FWHM	< 1 second	< 1 second	Useful for dichromography
Hard materials 2-D radiography					
Hard materials macro CT					
Hard materials micro CT					

The nature of the synchrotron beam means that large objects are often scanned through a fine 'slot' beam of radiation. This is not the case for absorption and phase contrast radiography on small objects, where the vertical divergence can provide reasonably flat beams of several millimetres height. The slot beam scanning means that a rectangular detector ($1 \frac{1}{2} D$) could be used with the

advantage of fast readout speed. No such detector has yet to be applied, although COTS do exist for belt scanning x-ray imaging. The resolution of these linear or 1.5 D arrays is currently too coarse.

One main difference between the materials and the biomedical imaging sciences is in the demand for small doses in tissue imaging. This means that the detectors must be highly efficient. Materials imaging does not have this constraint to anything like the same level.

Future trends

There is a strong trend in imaging to move to higher x-ray energies. This is true in both SR scientific areas represented at the meeting. Materials science benefits from greater penetration, and medical imaging by reduction in dose to the tissue whilst exploiting phase contrast. There is a dearth of detectors for the energy range of most interest which ranges from 50 keV to 150 keV. This is especially true for detectors with finer spatial resolution, for which there are science drivers in both areas. Both sciences are also looking to 3-D x-ray imaging which currently means computed tomography (CT). Medical imaging will certainly be interested in fluorescence CT in the longer term. It is likely that materials analysis will also benefit from this technique. CT often requires some 1500 projection images to be collected. In order to visualise dynamic processes the time scale for collection of this set needs to be of the order of 10 seconds. The size of the medical objects to be imaged will be of the order of 20 cm. Those in the materials imaging will be of the same order for macroscopic CT or a few millimetres for microtomography. The image resolution required in the case of medical imaging is around 10 microns. Materials science is currently using 1 micron and smaller resolution detectors. There will be a future driver to make this smaller, but primarily to retain this resolution at the higher energies.

Clearly the large number and fine resolution of these images will give rise to storage and data transport issues. Solutions to this might include configurable sensor arrays. Which can be tuned to provide resolution differences in areas of interest on the object. In line loss-less compression techniques should be investigated. Certainly as much as possible systematic noise from the system should be removed before storing the data. Although the Users will always want to keep all the data from an experiment or measurement, the data they keep should require no further processing before it is analysable for scientific results.

Future demands

Experiment	Image area	Image resolution	Exposure time	Time between images	Energy resolution
Medical 2-D radiography	> 200 mm by 200 mm	< 1 micron FWHM	< 1 second	< 10 Seconds	Useful for dichromography
Medical CT	> 200 mm by 200 mm	< 1 micron FWHM	< 1 second	< 1 second	Useful for dichromography
Hard materials 2-D radiography					
Hard materials macro CT					
Hard materials micro CT					

Technologies

Potential emerging technologies which could be employed in this direction are large area CMOS (Active Pixel Sensors) coupled to phosphors and photoconductors. Amorphous silicon arrays will

potentially become less noisy, so a watching brief should be kept on these. At the moment they use a phosphor, or a photoconductor as the detection material. There are developments afoot in vapour deposited Mercuric Iodide and Lead Iodide on these large area devices.

Detector materials research was brought up as an area where little direct work is going on for SR. There is likely to be gains for the high energy detectors in putting effort into researching materials with high stopping powers. The idea of

The status of image plate scanners was mentioned. They still have a place for static, low resolution imaging. A development specifically for SR imaging is unlikely but a watch should be kept on how the medical imaging market will push these types of systems.

A discussion on the hardware fixation issue was had (SHFS). The thought were that people trained in the hardware / software interface should be employed in the detector development teams. These people should be given the resources to ensure reliability and ease of use for the systems, which are likely to become ever more complex.

If pixel detectors can be made with appropriately small pixels (<10 microns) and with large areas (100 mms on a side) this would suit our needs. However we don't think that our science will drive this development.

Complex materials like biological tissue give rise to overlapping SAXS intensity distributions. The thesis is that disease gives rise to molecular structure change. Therefore the change in electron density distribution gives a subtle change in the SAXS pattern. Early experiments suggest these changes can be used for disease diagnosis in human tissues. There is currently no other x-ray source combined with hi-fi instrumentation that would allow this investigation to be pursued. These subtle changes can be analysed with multivariate techniques, providing the fidelity of the data is sufficient. A deal of care needs to be taken in collecting the data. The input beam flux, and transmitted flux need to be measured to better than 1% accuracy. The SAXS imaging system needs to be stable over periods of hours, and reproducible from one month to the next. These are tough goals, but have been met by the detectors DL developed 15 years ago.

The other area in medical use of SR x-rays that should be considered is various radiographies. There is strong evidence that tissue morphology can be imaged with very high energy x-rays using the phase change of the wavefront as it passes though the tissue. The use of higher energies keeps the radiation dose very small. Although the theory behind how the phase change gives rise to greyscale in the image is complex. Early results show that modelling the phase changes allow an electron density image to be calculated from the phase contrast image. The most effective energy is around 55 keV where the combination of the dose the tissue transmission and the detector efficiency produce a minima in a quality factor curve. Producing a detector that is high enough resolution, and efficient enough at 50-60 keV is no mean task. Ideally the clinicians would like resolutions down to the cellular level (10 microns) and below. But the samples are likely to be large, human knee size for instance. These requirements are likely to be met with a detector that has a built in zoom for small sections of its field of view.

Generic requirements

Data acquisition

The requirement for a reusable open-architecture data acquisition system underpins the all detector development. The importance of access to cost effective, easy to use electronics hardware and software is, in many cases, the make or break issue to getting a detector development used on a beamline effectively.

The approach to effective electronics hardware and firmware re-use has been addressed to some extent by work for the Particle Physics community.

For example the data acquisition requirements for development systems and many but the highest through put rate detectors can be met by 'Generic DAQ' cards developed for general purpose use. The cards have an industry standard format and PCI output bus that allows them to be plugged into commercial VME processor modules or into PCs. Each card incorporates 256 Mbytes of memory and two Altera 10KE30 Field Programmable Gate Arrays for data buffering and processing. Plug-in front-end cards have been developed that have 68 bi-directional LVDS digital channels or eight, 12 bit, 50MHz Analogue to Digital Converters. Other front-end cards can and will be designed. The Generic DAQ cards were designed to be built into scaleable systems and the requirements of more demanding applications, such as high rate pixel detectors, could be met by using larger numbers of cards. However this would not be the most efficient solution. The next generation of FPGA circuits offer features such as built in Power PC processors and 3 Gbit/s serial I/O that would dramatically increase the capacity of the data acquisition system. These devices open up new opportunities in data acquisition architecture including high speed serial data transmission from highly integrated front end circuits, real time data analysis, and integration with the beamline control and sample environment systems in high throughput or dynamic experiments.

A generic approach to design using FPGAs is required and is already being adopted in the UK SR community by Diamond, who will make extensive use of Generic DAQ. Electronics design blocks that are developed for one application using Generic DAQ will be made available for re-use in other areas. The aim is always to reduce the development time of such electronics systems and to give a greater flexibility of use.

The development of digital electronics designs that have a methodology that allows transfer between hardware platforms is a key concept to future digital electronics and again the lessons learned from Particle Physics will be key.

Front End Electronics

Many of the future detector systems are high channel count systems and this requires that Analogue front-end electronics will in many cases have to be designed in integrated circuit form from the outset. The use of integrated circuits is acceptable for a well defined system which has a single targeted goal, however costs, both in staff effort and fabrication, will be prohibitive to

making effective, crucial tests of a proof of principle system on a beamline early in the development process.

In many cases this problem has been addressed by use of front-end integrated circuits that have been developed elsewhere in the science community, notably Particle Physics to obtain a prototype system for trials. A notable use of this approach in the UK was the XSTRIP project. This project effectively used front-end i.c.s that had been developed for particle physics to obtain a good confidence level through beamline tests that allowed a detailed development programme to be costed and de-risked.

To effectively approach other developments may be more problematic as several of the future requirements for SR detectors will diverge significantly from where other science areas are going. Where there is commonality it would be best to both communicate and contribute to developments in these areas such that new i.c.s are known about. Where there is no other driving force within the science community it will be necessary to be closely coupled in to the world stage in SR detector development and also to develop some more generic front-end i.c.s which would be used for prototyping purposes.

These front-end i.c.s would be used for proof of principle experiments and so would not have to give ultimate performance or packing density. An example could be a set of i.c.s that would have a preamplifier chip that has some switchable gain and polarity settings to allow use on a variety of detector materials. A shaping amplifier chip which would allow initial processing of the front-end signal to a limited range of signal levels. A signal converter chip which would be a crude analogue to digital converter array. This would allow either a MCA function to be obtained at a compromised rate or a faster discriminator function to be achieved. Ideally this i.c. would have some programmable digital logic either on board or in close physical proximity.

This building block approach has many advantages early in the development cycle as it will enable the scientists to give early feedback to engineers about the proposed developments and will enable through de-risking the full development allow more accurate timescales and costings to be given.

Integration Technologies

These include wire bonding, bump bonding and mechanical assembly.

- Wire bonding, although a standard technology is for many systems proposed for future use not used in a standard way. As materials, other than silicon are used as detectors development will be required in this underpinning area to ensure that reliable, high density wire bonding can be achieved without introducing any artefacts from the process into the performance of the detector. This will include bonding to materials with fragile contact geometries and others that are required to work at cryogenic temperatures. Access to wire bonding facilities that can handle low volume, bespoke assemblies for rapid prototyping will be essential for many projects.
- Bump bonding. This area is crucial to many of the proposed future detector developments and still forms a high risk to the UK programme. Currently no access to bump bonding facilities for development is reliably available in the UK. This forms a major risk. The use of more exotic materials for detectors will be severely limited unless this aspect of detector assembly is addressed in a robust manner.
- Metrology and accurate assembly. This is an often-overlooked area in detector development but with more complex systems being built from the outset will require a greater degree of accuracy in assembly from the start. Accurate mechanical design, metrology and assembly will be key skills and technologies needed to support future developments.

- **Data acquisition**

The requirement for a reusable open-architecture data acquisition system underpins all detector development. Some of this system is already under development for particle physics, however specific requirements such as time stamping and continuous data flow will be necessary. For example the data acquisition requirements of development systems or lower rate detectors can be met by 'Generic DAQ' cards developed for general purpose use. The cards have an industry standard format and PCI output bus that allows them to be plugged into commercial VME processor modules or into PCs. Each card incorporates 256 Mbytes of memory and two Altera 10KE30 Field Programmable Gate Arrays for data buffering and processing. Plug in front end cards have either 68 bi-directional LVDS digital channels or eight, 12 bit, 50MHz Analogue to Digital Converters. The Generic DAQ cards were designed to be built into scaleable systems and the requirements of more demanding applications, such as high rate pixel detectors, could be met by using larger numbers of cards. However this would not be the most efficient solution. The next generation of FPGA circuits offer features such as built in Power PC processors and 3 Gbit/s serial I/O that would dramatically increase the capacity of the data acquisition system. These devices open up new opportunities in data acquisition architecture including high speed serial data transmission from highly integrated front end circuits, real time data analysis, and integration with the beamline control and sample environment systems in high throughput or dynamic experiments.

- **Imaging and spectroscopy.**

There are several areas that have underpinning detector technology requirements. These are identified under the scientific areas that follow. There is also a clear trend towards area detectors with energy resolution that can register a 2-D image of a material combined with spectroscopic or structural information at each pixel.

- **Energy resolution**

In many applications 1keV FWHM would be sufficient to eliminate harmonics, scatter and other artefacts. In more specific applications that require spectroscopy 250eV FWHM will be required for spectral line identification.

- **Count rate**

The high fluxes of the 3rd generation sources dictate we need to handle 10^8 photons /cm² with a spatial resolution approaching 150um for X-ray systems.

- **Efficiency**

While protein crystallography is centred about 12keV much of the engineering work requires higher energies to penetrate samples. We require at least 50% efficiency out to 150keV with minimal dead time introduced by the instrument itself. Additionally there should be only 1-2 pixel equivalent dead-regions on the detection area. This will allow effective image construction with image post-processing.

Glossary of terms

ADC	Analogue to Digital Converter
APS	Active Pixel Sensor (also MAPS)
CLF	Central Laser Facility
C-TRAIN	Germanium detector for spectroscopy
CZT	Cadmium Zinc Telluride
DAQ	Data Acquisition System
DIFFEX	One dimensional diffraction strip detector
FPGA	Field Programmable Gate Array
FWHM	Full Width Half Maximum
GaAs	Gallium Arsenide
GaN	Gallium Nitride
GMSD	Gas (Glass) Micro Strip Detector
HgI	Mercuric Iodide
HOTWAXS	High overall Through-put Wide angle X-ray Scattering Detector
HX2	128 channel Integrating readout chip for strip detectors
IMPRESS	Integrated Multichannel Preamplifier & Readout Electronics for Segmented Sensors
IR	Infrared
LVDS	Low Voltage Differential Signals
MAPS	Monolithic Active Pixel Sensor (silicon detector with integrated electronics)
MCP	Micro Channel Plate
RAPID	Multiwire fast Gas detector system
REES	Real Time Electron Energy Spectroscopy
SHAMROC	SHaper and Read Out Chip
SiC	Silicon Carbide
SLS	Swiss Light Source
SRS	Synchrotron Radiation Source (Daresbury Laboratory)
TEDDI	Tomographic Energy Dispersive Diffraction Imaging
UV	Ultra Violet
XAFS	X-ray Absorption Fine Structure
XAS	X-ray Absorption Spectroscopy
XCHIP	Chip for XSTRIP
XMCD	X-ray Magnetic Circular Dichroism
XSPRESS	X-ray Signal Processing Electronics for Solid State detectors
XSTRIP	1024 channel silicon detector for energy dispersive detection