Ultrafast-Detector upgrades

A long-standing issue in the synchrotron radiation community is that detector development has been lagging behind advances in other areas such as in accelerator physics, or beamline optics. With recent developments such as the Pilatus gateable area detector, or fast photodiode detectors, that gap has narrowed. However, the case can still be made that, for a given increase in beamline capability, detector development is often a more cost-effective way than accelerator improvement.

Synchrotron radiation is an important tool in the study of fast processes because, in addition to the atomic-scale spatial resolution, element specificity, and high penetration power of x-rays, its pulsed nature offers a natural time resolution of the order of 100 ps. Thus, an x-ray detector that can resolve the time between bunches (150 ns for the APS 24-bunch mode) is immediately capable of resolving 100 ps on a synchrotron.
There is also an increasing need to reach time scales faster than that, requiring advanced high-speed detectors, such as streak cameras or high-speed photodiodes.

Depending on the type of experiment, the optimum balance of detector properties must be found. A vigorous experimental program requires a wide selection of detectors.
Relevant detector properties are:

1) time resolution: slower / faster than 100 ns (bunch-gateable) / faster than 100 ps
2) energy resolution: none / several keV / 200 eV
3) photon yield: low / moderate / single-photon capable
4) dimensionality: pointlike / line array / 2d-array
5) gateability: no / yes

Streak-camera development:
(ultrafast, gateable, 0-d or 1-d, low photon yield, no energy resolution)
Streak cameras are the fastest general-purpose radiation detectors available. They work on the principle of rapidly sweeping an electron beam generated on a photocathode by the radiation of interest. The sweep introduces a spatio-temporal correlation that can be imaged with a conventional camera. Two types exist: single-shot/accumulating or synchroscan. The latter type are best for events occuring at high repetition rates, and can reach about 10 ps resolution. Single-shot/accumulating cameras are required for less frequent events, such as in laser pump, x-ray probe experiments, and also for few-picosecond resolution. With visible or ultraviolet light, time resolutions of a few hundred femtoseconds have been reported [1]. X-ray streak cameras are being developed at several universities and laboratories, worldwide, among them APS. One camera is installed as a user instrument at the 7-ID-C beamline of the APS, and efforts are ongoing to make improved streak-camera technology available to users. The main limitations of x-ray streak cameras are that 1) electron emission from photocathodes occurs from only a thin surface layer, which limits hard x-ray absorption to a few percent, at most, 2) the time resolution is limited to about one picosecond due to the energy spread of photoelectrons from x-rays.
Furthermore, the present x-ray streak camera at 7-ID-C is rather bulky, and can be used only for x-rays going in the forward direction of the synchrotron beam, i.e., not for general-purpose diffraction experiments. Finally, the laser optics next to the camera, which are needed for triggering the sweep and to provide a UV timing marker require special safety

precautions.
We propose to develop improvements of x-ray streak-camera technology, and to make streak cameras more user-accessible by:

1) improving the photon efficiency of photocathodes using nanostructured materials to increase the emission-active surface
2) implement electron-energy filtering/selection to mitigate the x-ray photoelectron energy spread
3) integrating the photoconductive switch into the streak camera to reduce pulse broadening by cable dispersion
4) design a compact x-ray streak camera that can be mounted on a detector arm. To facilitate operation of the mobile camera, the laser light to trigger the photoconductive switch will be delivered through an optical fiber, and all the laser optics will be integrated into the camera housing (see point 3, above) to permit operation by users without laser training.

This is a multi-year activity, which will require M&S of about 80k per year for 5 years.

Pixel-Array Photon Detectors, acquisition and development:
(gateable to 100 ns, 2-d, high photon yield, single/multi-photon, moderate energy resolution, large area/solid angle)
With recent advances in microelectronics, pixel-array detectors (PAD), where each pixel in a two-dimensional array contains signal-processing electronics, have become available. There are two types, photon-counting detectors that have threshold discriminators and event counters associated with each pixel, and analog detectors capable of multi-photon detection in each pixel. A well-known example of a first-generation photon-counting PAD is the Pilatus sold by Dectris [2]. This detector can be gated to select one bunch from the 24-bunch pattern of the APS, and is therefore suitable for experiments that require imaging and time resolutions down to about 80 ps (the APS bunch duration in 24-bunch mode). A 1-megapixel device costs about 500k$.

Another PAD, developed at Cornell University, gives signals proportional to the number of photons on each pixel. It is capable of storing multiple images on-chip, a capability that is needed to record very fast sequences of events that are not repetitive, and can therefore not be measured stroboscopically. An example would be the study of turbulence.
One detector with 1000 by 256 pixels costs about 1500k$.

In parallel to acquisition of a commercial device, the APS should team up with industry in the development of the next-generation PAD. SBIR-supported efforts are under way [3,4] to improve the time and energy resolution to a few ns and a few 100 eV, and more importantly to integrate the photodiode array with the signal-processing electronics in a single chip. This will eliminate the need for bump-bonding chips, which is a major weakness of the early-generation devices. The APS could play an important role in defining the features and characteristics of these detectors, and in testing them. Meetings with industry representatives have already taken place to determine how resources on the chips should be allocated for a general-purpose PAD.

Fast Photodiodes:
(sub-100-ps, 0-d or 1-d, small area, multi-photon, no energy resolution)

Small-area InGaAs photodiodes have been demonstrated [5] to yield about 1.5 ps timing jitter in laser-to-laser correlation with two independent diodes and a fast oscilloscope, and about 2.5 ps for laser-to x-ray correlation. The measured duration for laser pulses was clearly limited by the 13-GHz oscilloscope, and not by the diode. It appears thus likely that these commercially available photodiodes have the potential of resolving well within the APS bunch duration, using RF mixing techniques to go beyond the limitations of oscilloscopes. These photodiodes are, however, not single-photon detectors, needing about 10^3 x-ray photons for a good signal. The measured response of these small diodes to x-rays is slower than to laser pulses because the x-rays are longer, but possibly also due to the larger penetration depth of the x-rays, which leads to a spread of charge carrier diffusion times. A systematic study could identify commercially available photodiodes (telecom diodes) that have a faster response (quantum-well structures to limit the diffusion depth, etc.). For amplification of photodiode signals at bandwidths of 10s to 100s of GHz, the RF amplifier expertise of NASA and Caltech / Jet Propulsion Laboratory (JPL) can be tapped where such amplifiers are being developed for radio astronomy and satellite communications [6].

Avalanche Photodiodes:
(ns, possibly sub-100-ps, small area, moderate energy resolution)
Avalanche photodiodes can detect single x-ray photons because their internal gain boosts the signal level. Time responses of a few ns are easily achievable, and sub-ns response appears now possible [7]. These detectors should be tested at the APS to provide feedback to industry.

Proportional detectors for ultrafast spectroscopy:
(ns, no energy resolution, large solid angle)
X-ray fluorescence spectroscopy requires high-flux detection in a large solid angle. To go beyond the shot-noise limit, proportional detectors should be used. To discriminate between bunches, the time resolution has to be 100 ns, or better. This can best be achieved with plastic scintillators, as demonstrated at 11-ID-D. An important part of such a detection system is the data acquisition electronics, which must be capable of on-the-fly baseline correction, digitization-jitter elimination, and averaging.
M&S for 4 detectors (photomultipliers, amplifiers, scintillators): 50K
Fast digitizers with on-board signal-processing: 20K for 2 channels, 1Gsample/s

These detectors should be supplemented by energy-selective crystal optics that collect photons in a large solid angle. An example of such a device is the active-optic fluorescence-energy analyzer developed jointly at 7-ID and 11-ID-D [8].
One such device will cost about 40K, and multiple units (5-10) will be needed for maximum solid-angle coverage.

GHz infrastructure on time-resolved beamlines:
Beamlines involved in ultrafast detection, such as, specifically, 7-ID, need a good high-frequency-signal infrastructure:
permanently installed coaxial cables for at least 20 GHz: 20K
Oscilloscope, 10 GHz, or higher: 80K to 130K
Network Analyzer 30 GHz: 100 K .. 150K

Misc. RF components, amplifiers, mixers, adapters: 50 K

Overview of proposed expenses, capital only, no effort:

item	cost/unit (k$)	units	total (k$)
streak-cam. dev.	400	1	400
Pilatus PAD-1M	500	2	1000
Cornell-type PAD	1500	1	1500
pixel arr. det dev.			---
fast photodiodes			---
APDs			---
proportional det.			50
analyzer	40	5	200
GHz cables, adapters	70/beamline	1 (7-ID)	70
10-GHZ scope	120	1	120
network analyzer	150	1 (eq. pool)	150
total			3490

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