Compact pseudo-2D strip detector system for sub-meV IXS

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Abstract. A dual 32 strip sensor array is realized for use at the IXS (inelastic x-ray scattering) beamline of NSLS-II. By making use of established controls methods and sensor device recipes, our new geometry is realized quickly and at minimal cost. The detector geometry is chosen to match the output of a multi-element high-resolution energy analyzer, while the pulse thresholding is optimized for an ultra-low noise floor at a pass energy of 9.13 keV. Detector subsystems and integration are described, including sensor geometry and silicon device processing, cooling and thermal readback, bias and threshold optimizations, readout ASIC and controls, vacuum enclosure and x-ray window, mounting and positioning, and assembly procedure and testing.

1. Introduction
Inelastic x-ray scattering (IXS) presents unique challenges for detector development. In backscattering geometry, the detector is typically located near the sample, where space is limited; this constraint is compounded by the need for multiple sensor elements to support multiple analyzers or segments. Furthermore, in many IXS experiments where countrates can be particularly low, electronic noise and cosmic background must be fully suppressed.

Utilizing in-house capabilities for mechanical and electronics fabrication, a custom multi-pixel sensor system was undertaken to support the IXS beamline of NSLS-II [1] which makes use of a novel grazing-incidence backscatter scheme to achieve sub-meV resolution at 9.13 keV photon energy [2]. With first light anticipated in 2014, a rapid and low-cost detector development was pursued, providing the unique capabilities needed utilizing established detector capabilities at BNL [3].

2. Requirements
The geometrical requirements for the IXS detector system derive from the spectrometer optics, as illustrated in figure 1. In the IXS beamline, 5-10 mrad of scattered x-rays are collected from the sample using a multilayer mirror at 200 mm distance, which generates a 1-2 mm beam, collimated to within 100 μrad [4]. This collected beam is incident upon a set of three types of silicon crystals which includes collimator (C), dispersion element (D) and wavelength selector (W). The C crystal, reflecting asymmetrically, delivers an output beam of 21.5 mm in vertical extent per mm of incident beam size. Since a D crystal of 200 mm length, reflecting via grazing incidence back-diffraction, can accept no more than 1.2 mrad of equivalent collection from the mirror, the IXS beamline analyzer is designed to carry up to six D crystals in line, for a total acceptance of 7.3 mrad. After the D crystal reflection,
beam passes through the C crystal via anomalous transmission and is restored to its original size by the W crystal before finally striking the detector. This arrangement is designed to produce 0.7 meV bandwidth [1]. The detector’s energy resolution therefore is less critical than its geometry and thresholding features.

Lengthening the effective D crystal surface in this way yields an arrangement for the crystal analyzer assembly which is isomorphic to a dragonfly — with segmented abdomen, W as head, and C as thorax — so the IXS analyzer also bears this nickname. Since the reflection of each D crystal is independent, it is necessary that the detector separates the “beamlets” delivered from each.

As the IXS spectrometer is designed to support up to five such “dragonfly” analyzers, arranged side by side (multiple q option), a maximum of ~200 mm of horizontal extent is available for a detector system at each analyzer output location. The detector system must also avoid interference with beam incident to the analyzer, so it is constrained in vertical extent as well. Further requirements for the IXS detector system include high efficiency (>90%), low noise rate (<0.01 cps), energy resolution (ΔE/E) < 10%, and maximum count rate >20 kcps.

![Figure 1. IXS spectrometer optical concept.](image1)

![Figure 2. “Tagma” detector concept.](image2)

3. **Implementation**

Realization of the IXS Tagma detector system involves several subsystems as well as system assembly and test. Planning and execution of each element is briefly described in the following sections.

3.1 **Sensor Geometry and Fabrication**

To address the required isolation of the IXS analyzer beamlets, a custom sensor geometry was developed. A goal of no less than one unused sensor channel between adjacent beamlets was desired. Since the accepted 7.3 mrad is to be contiguous, a horizontal angle (ϕ) offset must be applied to each D crystal in order to ensure that adjacent beamlets do not share sensor elements. Consistent with this approach is the theoretical expectation that horizontal offset of 1±0.5 mrad is ideal for avoiding multiple beam losses near exact backscattering, with negligible energy shift [5]. Consequently, a total D-W-detector distance of 1 m results in a horizontal deflection of 2 mm at the detector plane. Likewise, shorter distances produce proportionally smaller offsets. By alternating the direction of the horizontal steering from one D crystal to the next, vertically adjacent beamlets can be made to land on either of two one-dimensional strips patterned side by side, as illustrated in figure 2. As each strip is 3 mm wide, a vertical pitch of 80 µm is selected to minimize interpixel capacitance (crosstalk and noise) while offering spatial resolution sufficient for the beamlet size (~244 µm V×1 mm H). Each beamlet is expected to occupy ~3 sensor channels (for 18 total) and to be separated by its neighbors by either unused channels or the central ground line, for maximum isolation. This pair of adjacent strips can be referred to as “pseudo-2D.” In the spirit of the “dragonfly” analyzer we also refer to this detector as “Tagma,” owing to its specialized grouping of segments into a coherently functional unit.

For maximum efficiency, the sensors were made from silicon wafers of 400 µm thickness (98% efficient at 9.13 keV), using an established P-on-N recipe. The IXS sensor geometry is included in a set of 6” wafer masks produced for a collection of similar sensors, including simple diodes and 640-
strip arrays. All process steps aside from ion implantation were performed in the cleanrooms of BNL Instrumentation. Aluminum window metallization thickness was 200-250 nm (>99.7% transmissive). Microscope inspection as well as I-V and continuity characterization was performed on candidate sensor chips to select units for system integration. The sensor chips include unpatterned areas for mechanical and thermal support.

3.2 Vacuum and Mechanical Assembly

Taking advantage of existing methods in high vacuum design, a set of three major mechanical parts were developed: a vacuum body with conflat nipple for mounting to the analyzer chamber, a cover plate with water-cooling and electrical feedthroughs, and a water-cooled copper block to support the sensor board. These three main parts were produced by BNL central fabrication facilities, with features added, complementary parts fabricated, and assembly completed by beamline technical staff. The copper block is supported from the cover plate in vacuum, and supports the sensor and electronics board; a rectangular hole is also included to let the x-rays pass into the sensor window. The vacuum body includes an o-ring groove (for 1/16” #47 size o-ring) to provide sealing to the cover. The cover plate includes compression fittings for water cooling tubes and a 37-pin electrical feedthrough (Detoronics DRTBH4-37P with 1/16” #29 size o-ring). An illustration of the assembly is provided in figure 3. Not included in this figure are the in-vacuum cables which fit tightly between the cover plate and sensor board; a conductive shield is also included to protect the sensor and wirebonds. The constraints on available space for the detector assembly for the IXS spectrometer have led to a design with minimum clearances (as small as ~2 mm) between components.

Figure 3. Tagma detector assembly (section view).

The copper water cooling block was assembled using soft solder and tested to 1 MPa (150 PSI) without failure, for use at 700 kPa (100 PSI). For assembly of the sensor board to the copper block, an intermediate copper sensor support frame is used, which supports the sensor chip atop a pair of thermoelectric Peltier coolers (TE Technology TE-2-(31-12)-1.0, wired in series) which in turn rest on the water-cooled block. The combined height of coolers and small frame are matched by the depth of the mating surface within the large block in order to maintain the sensor and board at the same height. A pair of 10 kΩ thermistors attached to both copper parts offer temperature readback for the sensor and bath. Good thermal contact at interfaces (sensor to frame to Peltier to copper block, thermistor to frame and copper block) is ensured using a high-resistivity, high-thermal conductivity epoxy (EG-7658), cured for 2 hours at 100 °C.

3.3 Board Design and Integration

Sensor readout is provided via the HERMES 4 ASIC [3] which amplifies, filters and counts photon pulses, with 32 channels per chip. It can count up to $10^5$ pulses per second per channel, and offers both upper and lower thresholds. A custom board was developed to support sensors requiring only two such ASIC readout chips, for 64 total channels. This board provides signal conditioning for HERMES control and readout, as well as bias and temperature control. It connects via ribbon cable...
through the vacuum feedthrough to a standalone EPICS control unit which is addressable over Ethernet. The control unit also supplies high voltage for sensor bias and low voltage (current) for the thermoelectric coolers, and provides inputs for test pulses as well as analog output from a selectable channel for diagnostics.

3.4 System Test
The complete detector system pumps to a typical base pressure of $10^{-6}$ mbar. With a bath temperature of 12 °C, thermoelectric cooler current of 0.5 A provided a sensor temperature of -35 °C. Illumination was provided by NSLS beamline X16A, a test beamline outfitted to perform basic x-ray optics tests using a bending magnet source and Si(111) monochromator. The photon energy of the beam was 9.1 keV, collimated to less than 100 µrad and 10-20 µm beam size. The detector was mounted to a 4-axis positioner, with vacuum tee fitted to the conflat entrance port to provide vacuum pumping and gauging as well as use of a beryllium x-ray entrance window. For data acquisition, integration to spec (certif.com) was provided via a macro named hermes.mac which integrates data capturing and zeroing into the standard accumulation sequence.

Detector bias was set to 120 V based on electrical tests. Global threshold was optimized manually, yielding a noise count rate of 11 counts per 1000 seconds over all 64 channels (0.6 counts per hour per channel); since only 18 channels are expected to be used, the total noise count rate can be expected to be as low as 11 counts per hour (0.003 cps).

To characterize detector energy resolution, a multichannel analyzer was used to collect spectra from the analog output for typical sensor channels under synchrotron beam illumination of individual sensor strips. FWHM for low-rate, single photon pulses (~10 cps) was typically ~8% of the peak position (750 eV at 9.1 keV), as shown in figure 4.

4. Summary
A custom detector system, complete with cooling, vacuum enclosure, and controls was produced and tested within 10 months utilizing roughly 1 person-year of labor, by making efficient use of existing in-house designs and facilities. The demonstrated performance satisfies the requirements for NSLS-II IXS beamline, providing the required spatial resolution (80 µm pitch, 6 mm size), efficiency (98% efficiency for 400 µm silicon), low noise (0.003 cps), energy resolution ($\Delta E/E$ of 8%) and maximum count rate (100 kcps/ch over 18 channels for more than 1 Mcps total).

Future improvements to come include pixel-specific threshold trim automation and graphical data integration to the beamline control and acquisition system.

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