Beam synchronous detection techniques for X-Ray spectroscopy

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Abstract. The Photo diode detectors combine a set of properties that make them most appropriate, in particular, for X-ray Magnetic Circular Dichroism (XMCD) experiments. Under standard operating conditions, the detection bandwidth is primarily limited by the transimpedance preamplifier that converts the very low ac photocurrent into a voltage. On the other hand, when the photodiode is reverse biased, its finite shunt resistance will cause an undesirable, temperature dependent DC dark current. The best strategy to get rid of it is to use synchronous detection techniques. A classical implementation is based on the use of a chopper modulating the X-ray beam intensity at rather low frequencies (typically below 1 kHz).

Here we report on the recent development of a fast X-ray detection which has the capability to fully exploit the frequency structure of the ESRF X-ray beam (355 KHz and its harmonics). The availability of new wide band preamplifiers allowed us to extend the working frequency range up to a few MHz. A beam synchronous data processing was implemented in large FPGAs. Performances of the new detection system implemented at the ESRF beamline ID12 are illustrated with detection of the Fe K-edge XMCD spectra in garnets, using 4 bunches operation mode with modulation frequency of 1.4 MHz.

1. Photo diodes for spectroscopy.

X-ray Magnetic Circular Dichroism (XMCD) is always a very small effect, often lying in the $10^{-3}$ to $10^{-4}$ range with respect to the main fluorescence signal [1]. Detectors for these experiments must therefore provide high dynamic range and linearity. In the case of XMCD, they also have to be ultra high vacuum compatible and insensitive to high magnetic field. This set of constraints make photo diodes particularly attractive for such applications.

Photo diodes are traditionally considered as DC current sources. When coupled with large feedback transimpedance amplifiers, they provide high dynamic range and linearity with good signal over noise ratio. S/N can further be optimized by reverse biasing the diode, thus reducing the detector capacitance but increasing its DC dark current, noisy and temperature dependant (examples in [2]). Improving the measurement accuracy by time integration eventually makes the whole experiment sensitive to drifts.

Theses constraints led us to introduce synchronous detection in the processing by modulating the beam with a low frequency chopper.
The voltage to frequency converter at the amplifier output implements a very simple digital integration of the signal. Synchronously counting with the “beam” and “no beam” phases available from the chopper allows removing the baseline drifts from the signal by subtraction. The chopper frequency lies in the 100 Hz range, compatible with high gain amplifier bandwidths. Source modulation actually translates the signal (together with the source noise) to a frequency where the additive noise (detector + amplifier) is generally lower, therefore improving S/N (fig. 2). Furthermore the synchronous detection efficiently filters all noise components outside the modulation frequency.

Using a beam chopper has some drawbacks: jitter, frequency limited modulation, and loss of half the source photons available.

2. Beam synchronous detection.
Synchrotron radiation is naturally modulated, as a consequence of both the bunch structure of the beam and the storage ring filling pattern.

2.1. Frequency structure of the ESRF beam.
At ESRF the fundamental bunch frequency (bunch repetition rate) is 352.202 MHz. With 992 bunch locations distributed along the ring, the ring frequency is 352.202 MHz / 992 = 355.04 KHz. Depending on the filling pattern, the frequency structure can be quite variable. Table 1 below summarizes the most common filling modes together with their associated fundamental frequency.

If we except the uniform filling mode, all other modes exhibit fundamental beam modulation frequencies in a few MHz range. These values are easily compatible with the implementation of digital techniques to process the signal with front end ADCs.
Table 1. Fundamental beam frequencies at ESRF.

| Filling mode | Fundamental beam frequency |
|--------------|-----------------------------|
| uniform      | 352.202 MHz                 |
| 7/8          | 355.04 KHz                  |
| 4 bunches    | 1.4 MHz                     |
| 16 bunches   | 5.6 MHz                     |

2.2. *Principles of beam synchronous detection.*
Sampling is the multiplication of a signal by a periodic Dirac. Therefore the necessary multiplication for the demodulation of the beam frequency contained in the photo diode signal can be efficiently implemented in an ADC, provided that the sampling frequency is appropriately selected.

With a sampling frequency equal to N times the beam modulation (N integer), samples come distributed along N fixed positions on one period of the modulated signal. Accumulating samples on these N positions over successive signal periods averages out all non correlated noise components and eventually yields a noiseless picture of the signal period. Choosing $N = 2^p$ simplifies the FFT calculation to obtain the signal amplitude.

This particular implementation of a digital lockin comes with decisive advantages over traditional analog lockin amplifiers:
- No lockin issue: the system is naturally locked, independently of the signal level.
- No sensitivity to the modulation and signal shapes: the digital system returns the true signal shape and all its harmonics (as far as the sampling frequency allows).
• Easy to implement and versatile, due to the use of FPGAs for the processing.

2.3. Implementation.
A 4-channel electronic board in compact PCI format has been designed and is currently installed on ID12. It has a programmable gain input stage, 12 bits fast ADC and a large XILINX FPGA supporting application dependent configurations. Usual operating values: signal: 355 KHz, sampling frequency: 11.36 MHz, preamplifier bandwidth > 1 MHz.

2.4. Results.
Performance is illustrated below with Fe K-edge XMCD spectra in garnets.

![Figure 4: comparative test: beam chopper vs beam synchronous detection.](image)

On figure 4 the dotted line is the fluorescence pre edge. The XMCD measurement accuracy obtained with beam synchronous detection at a high modulation frequency (1.4 MHz) with a low power source (4 bunches), is at least as good as that obtained with classical electronics, beam chopper and a multibunch filling mode for the same acquisition time.

2.5. Extensions.
A new spectroscopy called XDMR, first introduced by J. Goulon in [3], has been developed on ID12. Synchronous detection techniques have extensively been used to measure the extremely weak XDMR signals where several modulations bands are extracted from noise with a vector spectrum analyser (AGILENT 89600 series). Details on these new instrumentation schemes can be found in [4].

A faster and multi-frequency version of the in house acquisition board is also under development.

References
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