ULTRA HIGH-SPEED DETECTOR FOR SYNCHROTRON RADIATION RESEARCH

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Motivation

Many experiments at 3rd (soon 4th) generation synchrotron radiation sources only possible with GHz-rate linear detection of electrons or photons, leading to:

- 100-1000x faster data rates than presently possible:
  - *E.g. time-resolved photoelectron spectroscopy, diffraction, holography*
- More efficient beamtime usage:
  - *No need to reduce photon flux/close slits to avoid non-linearity and saturation*
- Higher quality data:
  - *Better linearity, minimize after-the-fact corrections*
- New experiments:
  - *Time-resolved photoemission, Soft x-ray resonant magnetic scattering & X-ray emission spectroscopy*
  - *Real-time energy dispersive, transmission x-ray absorption spectroscopy*

Approach

- Build upon high energy physics detector technology
- Use custom integrated circuits for many-channel MCP readout
- Analog front-end (CAFE-M from ATLAS)
- Counter and binary readout: custom-designed BMC chip for deadtime-less readout
- ALS High-Speed Detector Version 1 demonstrated principal
- Improved High-Speed Detector Version 2:
  - *More robust design*
  - *Increased count rate capability*
  - *Reduced size to fit existing spectrometers*
  - *Improved (faster) readout system*

Comparison with Existing Detectors

Detector	Channel width (μm)	Energy resolution ΔE/E (x10^-4)	No. of channels	Maximum overall countrate	Comments/features
1D – LBNL (Detector 2—present)	48	1.3	768	> 1.1 GHz	Low noise, linear, ultra-high rates
1D – Elettra	320	8.0	96	~5 MHz?	In use, slower
1D – Aberystwyth	25	0.7	192	~20-40 MHz	Ions, 10-20x lower sensitivity for electrons
1D – Specs	~1000?	Low	9	90 MHz	Fast, but few channels
2D – CCD (Scienta)	110x110	2.9	360x360	< 1 MHz	Non-linear over full range
2D – Resistive anode (Quantar)	400x400	10.0	256x256	<1 MHz	Linear to ~ 300 kHz

Summary and Outlook

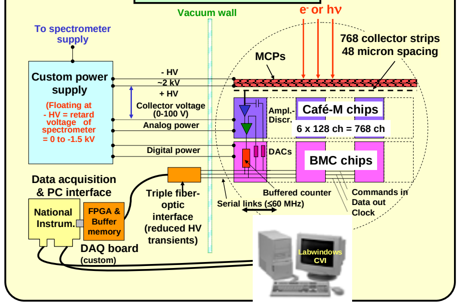
Current Evaluation of Performance:

- Spatial Resolution: ~100 μm (~2 channels), probably better
- Data readout: 200 μs with buffer memory (in progress)
- Linearity: linear up to 1.4 MHz/Channel → 1.1 GHz total
- Size: small enough to fit existing spectrometers (Scienta, PHI,...)
- Stability and Reliability: working at the ALS BL4 since 06/29/03
- Bakeable up to 100 degree C → UHV compatible

Some future experiments:

- Minutes → seconds photoelectron diffraction/holography for surfaces & nanostructures, time-resolved valence-band spectroscopy
- Time-resolved surface reaction studies: steady-state or pump-probe
- Time-resolved magnetization studies, incl. MCD
- Other applications: time-resolved near-edge x-ray absorption fine structure
- Laser spectroscopy with visible/IR photocathode on MCPs

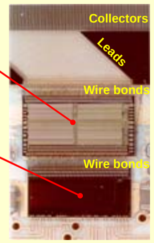
Detector Architecture



Custom Integrated Circuits

CAFE-M, analog front end:
Gain at the Comparator 100 mV/fC
Peaking Time 25 ns
Output Pulse Amplitude 100 μA
Double Pulse Resolution (Qs=4 fC) 50 ns
Time Walk (Qs=1.25 - 10 fC) < 15 ns
Supply Voltage 3.5 V
Power Dissipation per Channel 1.2 - 1.8 mW
Number of Channels 128
Includes calibration pulse generator

BMC (Buffered Multichannel Counter):
Counter sizes (selectable) 4,8,12,16,24-bit
Maximum counting frequency >2 MHz/channel
Serial link operating frequency >40-60 MHz
Supply Voltage 3.3 V
Power Dissipation (total) 45 mW
Number of Channels 128
Includes dual 8-bit DAC for CAFE-M control & internal test functions



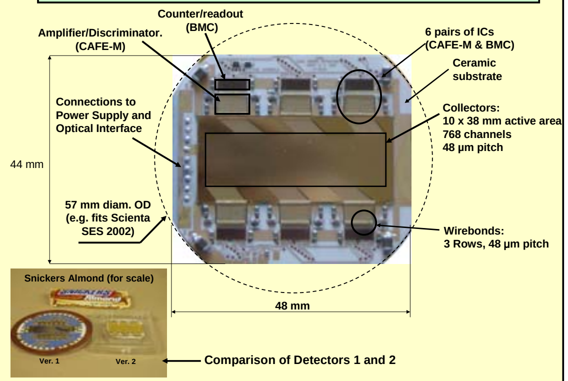
Publications

J.-M. Bussat, C.S. Fadley, Z. Hussain, A.W. Kay, G. Lebedev, B.A. Ludewigt, G. Meddeler, A. Nambu, M. Press, H. Spieler, B. Turko, M. West, and G. Zizka, American Institute of Physics Conference Proceedings 705, 945 (2004).

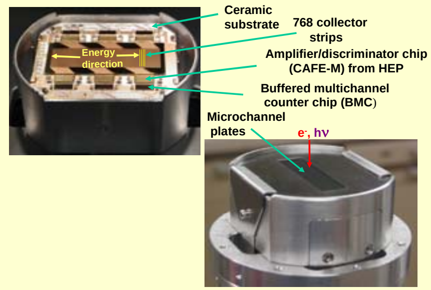
A. Nambu, J.-M. Bussat, B.C. Sell, M. Watanabe, A.W. Kay, N. Mannella, B.A. Ludewigt, M. Press, B. Turko, M. West, G. Meddeler, G. Zizka, H. Spieler, T.Ohta, Z. Hussain, C.S. Fadley, Journal of Electron Spectroscopy and Related Phenomena, 137-140, 691 (2004).

J-M. Bussat, C. S. Fadley, B. A. Ludewigt, G. J. Meddeler, A. Nambu, M. Press, H. Spieler, B Turko, M. West and G. J. Zizka, to appear in IEEE Nuclear Transactions, in press (2004).

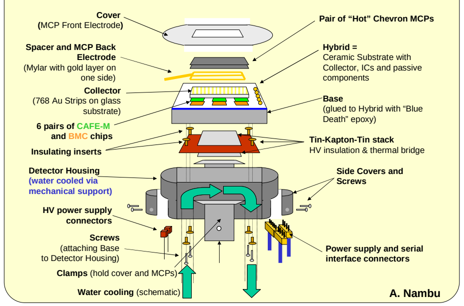
Ceramic Substrate, Collector, ICs – the Heart of the Detector



Detector Assembly

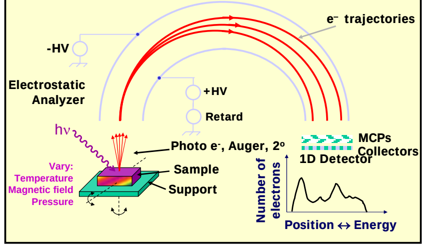


Exploded View of Assembly

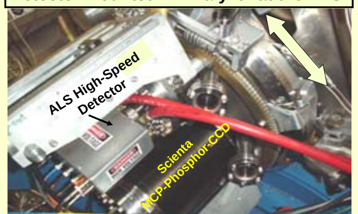


Configuration

Detection in Electron Spectroscopy



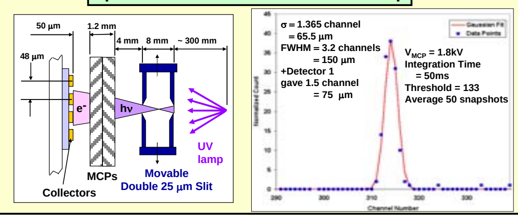
Detector Mounted in Analyzer at the ALS



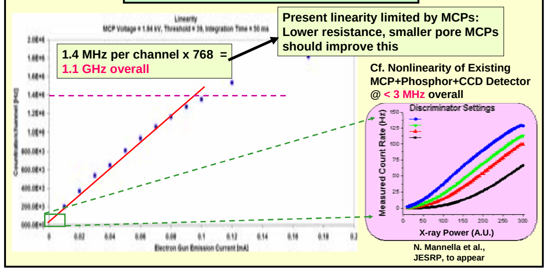
Detector Carousel--Two Interchangeable Detectors

First Test Results

Spatial Resolution: Test with UV Lamp

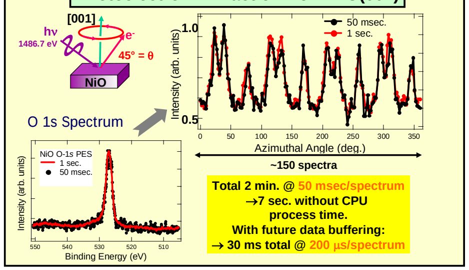


Linearity Check with Electron Gun



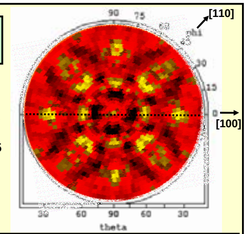
First Experimental Data

Photoelectron Diffraction from NiO(001)



Total 2 min. @ 50 msec/spectrum →7 sec. without CPU process time.
With future data buffering: → 30 ms total @ 200 μs/spectrum

Photoelectron Holography



NiO(001), O 1s emission
Conventional x-ray tube (Al Kα), ~1700 spectra, 35 min total

Ultrahigh-Speed, One-Dimensional Detector for Synchrotron Radiation Experiments

(Advanced Light Source, LBNL, June, 2004)

An ultrahigh-speed (~1.5 GHz), one-dimensional detector array for electrons and vuv/soft x-ray photons is just completing development at ALS/LBNL. This advanced detector should be capable of handling the highest count rates encountered at third-generation synchrotron radiation sources, thus permitting the fullest utilization of the radiation, as well as new kinds of time-resolved experiments. The detector is also free from low-countrate non-linearity problems that have been encountered in the past with CCD detectors, and it pushes the upper end of linear counting upward by factors of approximately .

Electrons or photons are detected and counted by a state-of-the-art configuration of microchannel plates, a finely spaced array of charge collection electrodes, and custom-designed integrated circuits and interface logic (see Figure 1). The electrons or photons impinge on a pair of multichannel plates in a chevron configuration. The active counting area in the first version to be built is 38.4 mm by 10 mm. The charge clouds emitted from the backside of the channel plate are collected on 768 collection strips with 48 micron spacing that are wire bonded to 6 pairs of signal processing ICs. Each frontend IC (the CAFE-M, a proven device from high energy physics [1]) has 128 channels of amplifiers and discriminators. The vpulse-pair resolution is 50 ns and this leads to an estimated maximum linear countrate/channel of 2 MHz; this rate is about 10 times slower than the inverse of the pulse-pair resolution time to minimize pulse pileup, which should be about 10% at this rate. This yields an overall countrate ot 768 x 2 MHz or ~1.5 GHz. The frontend IC is followed by a custom-designed buffered multichannel counter (BMC) IC permitting readout with no deadtime. The BMC IC features a 24-bit buffered counter for each channel, programmable control of CAFE-M threshold levels and calibration signals, and a serial link for the transfer of commands and data.

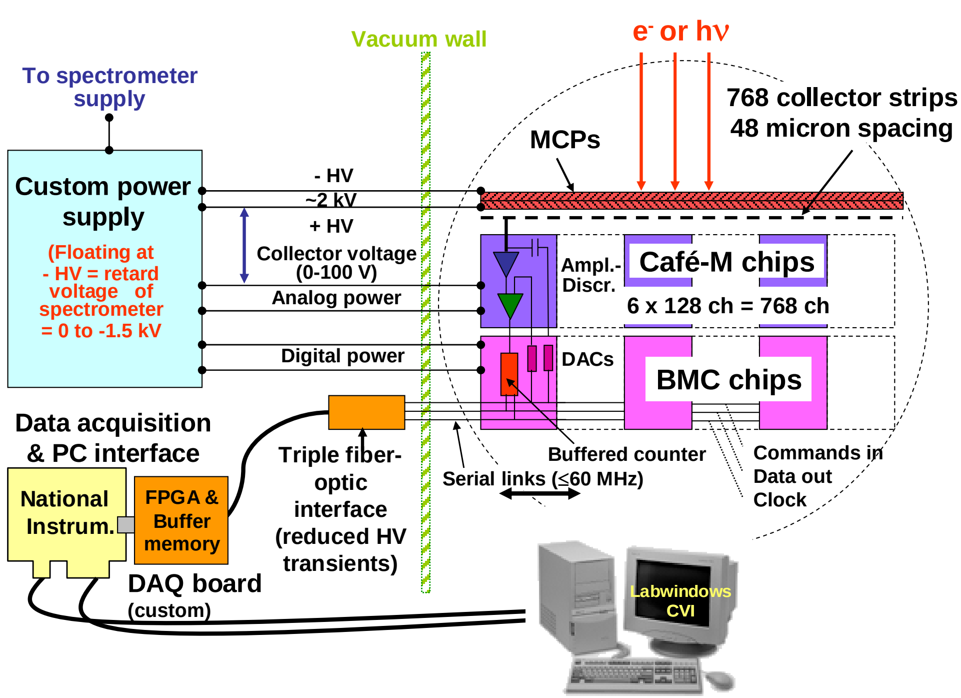


Figure 1: Ultrahigh-speed detector system schematic

The detector is assembled on a ceramic substrate using clamps to hold the multichannel plates in place above the collector (see Figure 2). Wirebonds connect collector strips and ICs. The assembly is surrounded by a protective shell with an outside diameter of approx. 65 mm for fitting into a SES 2002 analyzer. (A second, smaller version of the detector could be designed for use with the SES 100 analyzer or other smaller analyzers. This version would feature 512 channels connected to 2 pairs of signal processing ICs. Its active area would be 25.6 mm x 10 mm.)

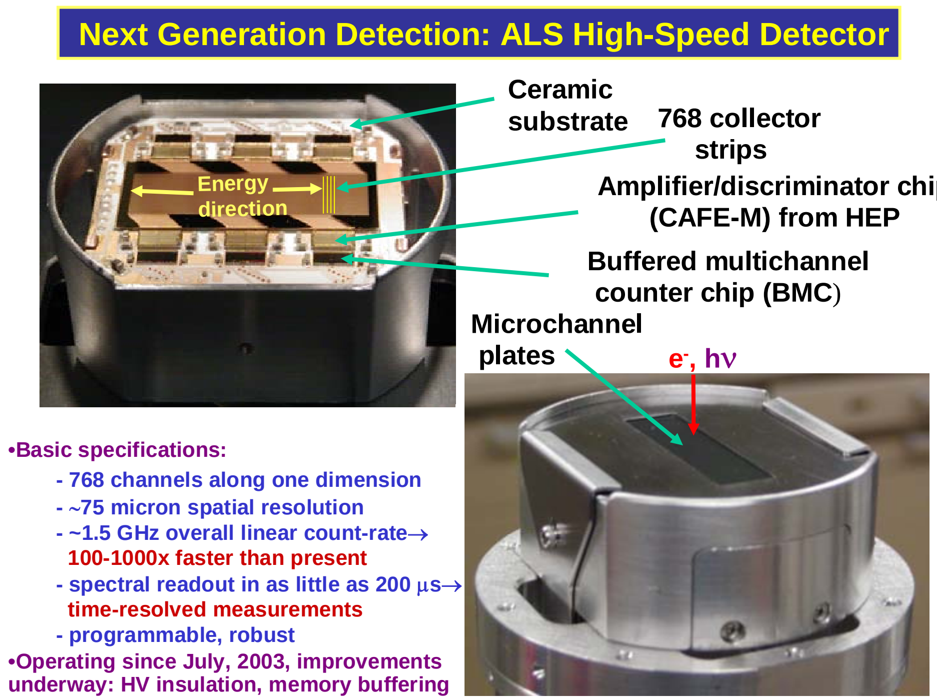


Figure 2—Detector mechanical configuration

The detector can float at high potential with respect to ground if needed, in particular at the retarding potential of an electron spectrometer. This float potential can be up to 2 kV, In order to avoid high voltage damage to ICs and other components, as well as unwanted noise via ground loops, the serial command and data lines are connected to the data acquisition system via three optical fibers. The detector is thus protected against high voltage failures such as a short from detector common to ground. A special field programmable gate array (FPGA)-based interface residing on the PC-side of the opto-interface board serializes and parallelizes the commands and reads out data, respectively. A National Instruments board is used as the PC interface. The system is operated with a LabWindows/CVI-based software.

This detector will thus be able to count approximately 100 times faster than any other present detector, with significantly improved spatial resolution of 75-100 microns as well. The data transfer speed to the interface will be up to 60 Mbits/s. The number of bits to be read out from each counter is programmable. For fastest readout in time-resolved experiments, a smaller number of bits can be chosen making it possible e.g. to complete a spectral readout at 4 bits precision in ~ 150 μs for a 40 MHz operating frequency (serial clock).

A previous prototype of this detector, which was outfitted with less capable readout ICs, has already demonstrated the ability to count linearly at up to 1.0 GHz overall, to resolve channels with a FWHM of 75 microns, and to operate in a typical UHV ALS environment (see attached contribution to the ALS Compendium of Abstracts for 2001). More recent publications describe the second version to be described below [2-4].

A first detector of this second type was mounted in an SES 200 electron spectrometer in the Fadley end station at the ALS in July, 2003, and has proven capable of taking data in a real synchrotron radiation experimental environment. The overall mounting mechanism of this detector is shown in Fig. 3, including provision for water cooling and a rotation mechanism for precise alignment of the collector stiips with the spectrometer energy dispersion.

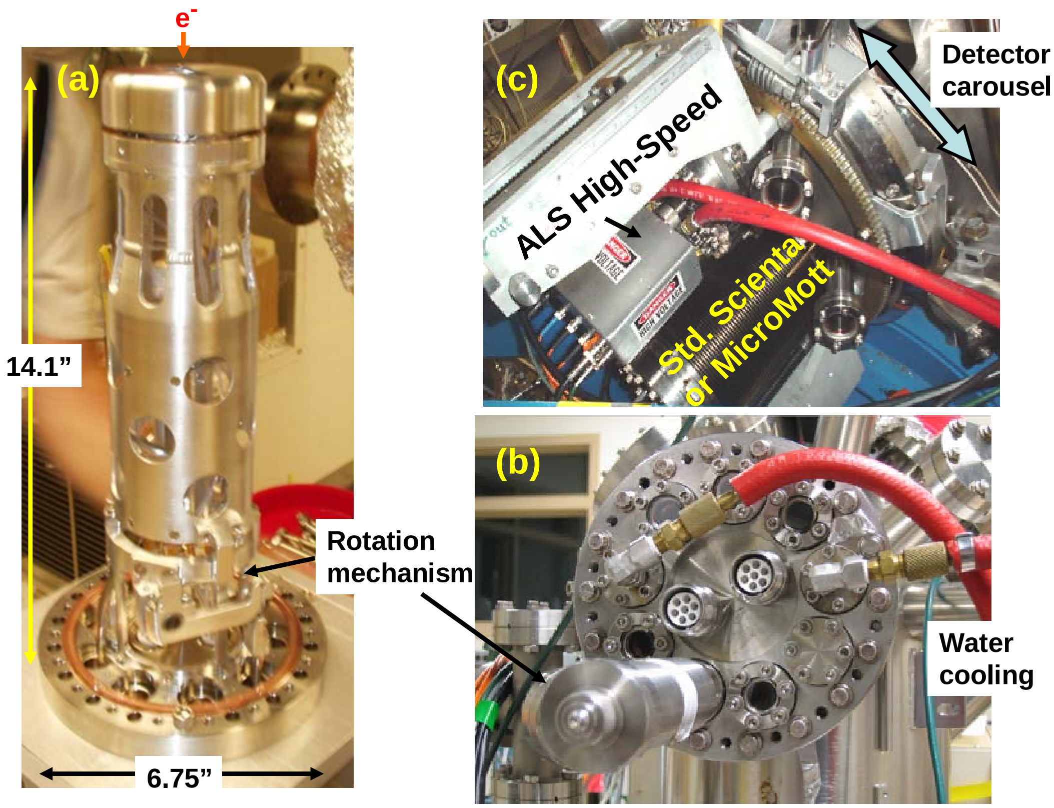


Figure 3—Mechanical mounting of the ALS High Speed Detector

Some demonstration photoelectron diffraction data from NiO obtained within the past few months are shown below in Fig. 4. Here, the primary limitation on the speed with which a given snapshot spectrum could be obtained was the PC processing time for handling the data; this will be eliminated as a source of delay with the interface buffer memory that will be completed in summer, 2004. Three papers have so far been published on this detector and the first experimental data obtained with it [2-4].

As of June, 2004, we are working to eliminate a weakness in the high-voltage insulation external to vacuum that has caused occasional shutdowns, and to finish a buffer memory system that will permit spectrum accumulation in 150-200 μs, provided that 4-bit accuracy is sufficient, e.g. in some type of time-averaged pump-probe measurement. Only the software for the latter development remains to be completed. Other detectors will be fabricated once these things are completed and the current system is fully tested and certified.

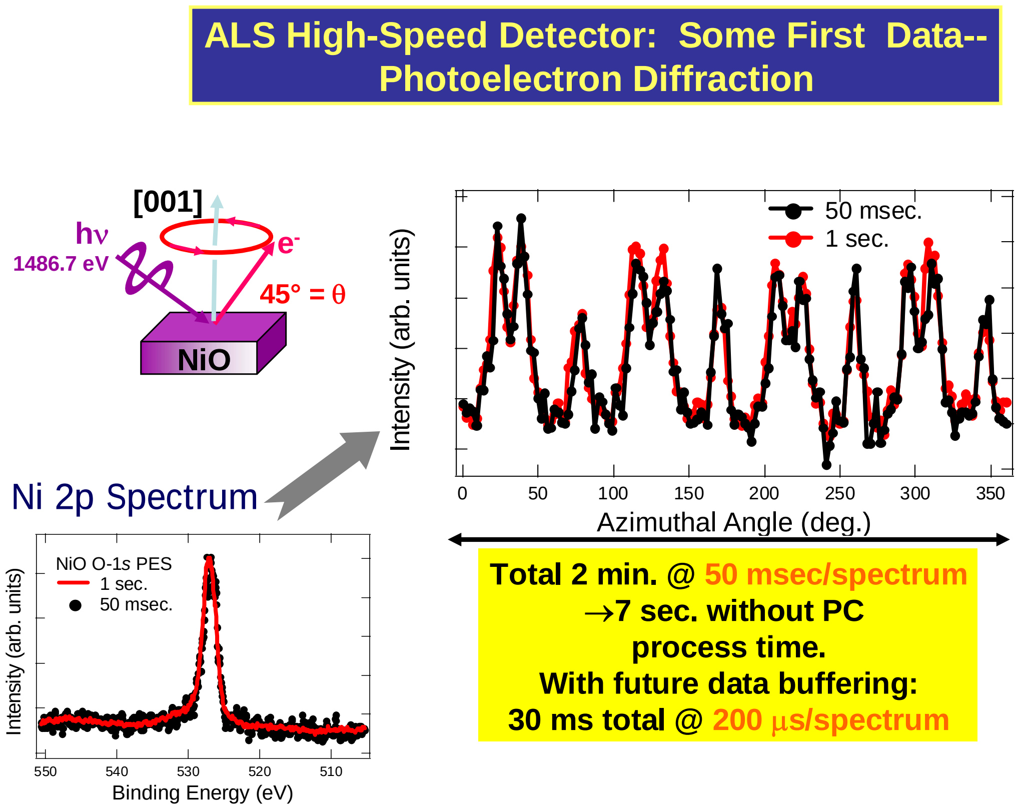


Figure 4—Some first experimental data: Photoectron diffraction from NiO(001)

<u>Overall Detector Design Parameters and Features:</u>

Active detector area:	38.4 mm x 10 mm (second version at 25.6 mm x 10 mm)
Number of channels:	768 (second at 512)
Channel separation:	48 μm
Actual spatial resolution in 1D	~75 μm FWHM (tested directly with a collimating slit assembly)
Maximum linear countrate/channel:	2 MHz

Maximum tota linear countrate for detector: 2 GHz for 768 channels (1.3 GHz for 512 channels) ????
Buffered 24 bit counter for near deadtimeless readout
Selectable (programmable) number of bits for fast readout: 4, 8, 12, 16, or 24 bits

Readout time:	150 μs to 1 ms
Overall detector size:	65 mm outside diameter (fitting SES 2002) (second version at approx. 48 mm outside diameter for smaller analyzers)

As part of this R&D effort, LBNL can build (under a work-for-others contract) <u>a limited number</u> of complete systems for collaborating laboratories. This would be done on a first-come/first-served basis. A complete system would include the detector module, the fiberoptic link, the computer interface, software for control and data acquisition, the power supply system, and a set of documentation and instructions for detector operation and testing. In-house training of personnel from contracting laboratories via collaboration with LBNL scientists could also be arranged.

Cost of a complete detector system: Estimated cost of $160 K for 65 mm o.d., with additional R&D cost for a 48 mm o.d. system

Delivery: Estimated within 9 months for 65 mm o.d.: 6 months fabrication and 3 months for testing

Additional information can be obtained from:

1. Bernhard Ludewigt, Staff Scientist: Bernhard_Ludewigt@lbl.gov
2. Zahid Hussain, Staff Scientist: ZHussain@lbl.gov
3. Chuck Fadley, Faculty Staff Scientist: fadley@physic.ucdavis.edu

References:

(1) Kipnis, H. Spieler and T. Collins, A Bipolar Analog Front-End Integrated Circuit for the SDC Silicon Tracker, IEEE Trans. Nucl. Sci. NS-41/4 (1994) 1095-1103; A. Ciocio et al., A Binary Readout System for Silicon Strip Detectors at the LHC, Proceedings of the First Workshop on Electronics for LHC Experiments, Lisbon, September 11-15, 1995, CERN/LHCC/95-56, 108 - 113; F. Albiol et al., Performance of the ATLAS Silicon Strip Modules, Nucl. Instr. and Meth. A403 (1b998) 247-255; T. Dubbs et al., The Development of the CAFE-P/CAFE-M Bipolar Chips for the ATLAS Semiconductor Tracker, Proc. 5th Workshop on Electronics for the LHC Experiments (LEB 99), Snowmass, Colorado, 20-24 Sep 1999, 123-127.

Papers dealing specifically with the detector discussed here:

(2) "An Ultra-High-Speed Detector for Synchrotron Radiation Research", J.-M. Bussat, C.S. Fadley, Z. Hussain, A.W. Kay, G. Lebedev, B.A. Ludewigt, G. Meddeler, A. Nambu, M. Press, H. Spieler, B. Turko, M. West, and G. Zizka, American Institute of Physics Conference Proceedings 705, 945 (2004). (Proceedings of SRI 2003, San Francisco, CA)

(3) "An UltraHigh-Speed One-Dimensional Detector for Use in Synchrotron Radiation Electron Spectroscopy: First Experimental Results", A. Nambu, J.-M. Bussat, B.C. Sell, M. Watanabe, A.W. Kay, N. Mannella, B.A. Ludewigt, M. Press, B. Turko, M. West, G. Meddeler, G. Zizka, H. Spieler, T. Ohta, Z. Hussain, C.S. Fadley, Journal of Electron Spectroscopy and Related Phenomena, 137-140, 691 (2004). (Proceedings of ICESS9, Uppsala, Sweden).

(4) A Next Generation, High Speed Detector for Synchrotron Radiation Research, J-M. Bussat, *Member*, C. S. Fadley, B. A. Ludewigt, G. J. Meddeler, A. Nambu, M. Press, H. Spieler, B Turko, M. West and G. J. Zizka, to appear in IEEE Nuclear Transactions, in press (2004).

Attachment: Contribution to the ALS Compendium of Abstracts for 2001

(Contribution to the Advanced Light Source Compendium of Abstracts, 2001)

Development of a GHz-Rate Detector for Synchrotron Radiation Research

B. Turko[3], M. Press[3], A.W. Kay[1,2,#],. M. West[1,3], J.E. Katz[3], H. Spieler[5], Z. Hussain[4], C.S. Fadley[1,2], B. Ludewigt[3], J.-M. Bussat[3], P. Denes[3], H. von der Lippe[3], G. Meddeler[3], G. Zizka[3], G, Lebedev [4], M. Mellon[6], T. Wiell[7]

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INTRODUCTION

It has by now become obvious that the brightness of third-generation synchrotron radiation sources often exceeds the capabilities of the end-station detector systems to adequately handle the electron or photon fluxes resulting from a given experiment, thus preventing both the fullest utilization of the radiation and the carrying out of certain new types of experiments readily, if at all. Detector non-linearity is one problem that has been encountered [1], but there are many other examples for which beamline or spectrometer throughput must be decreased to prevent high countrate saturation, or the number of energy or angular channels that can be counted simultaneously severely limits a given experiment [2]. In recognition of this, a national-level initiative in detector development has been proposed by the multi-institutional "DetectorSync" group [2].

As a first example of what can be accomplished with advanced detector technology, a project to develop an ultrahigh-speed one-dimensional detector for electrons and vuv/x-ray photons is underway at the ALS.

DESIGN PHILOSOPHY AND FIRST TEST RESULTS

This project takes advantage of unique expertise at LBNL for detector development in high-energy and nuclear physics, and involves the custom design and fabrication of application-specific integrated circuits (ASICs). The final goal is a 768-channel detector with 50 micron spacing between channels and a maximum linear countrate per channel of over 2 megaherz. The overall countrate will thus be in the 2 GHz range, and approximately 100 times faster than any other present one-dimensional or two-dimensional detector, with significantly improved spatial resolution as well compared to other existing detectors. First applications will be in electron spectroscopy, but others in x-ray absorption and x-ray emission spectroscopy are expected to follow.

A first prototype of this detector is shown in Fig. 1(a). Based on 12 pairs of 64-channel ASICs (an existing high-energy preamplifier chip (SDC) and a specially-designed buffered counter (DBC)), this detector has already demonstrated the ability to take spectra in a Scienta electron spectrometer located at the ALS (Fig. 2(a)), to resolve channels with a FWHM of 75 microns (Fig. 2(b)), and to count linearly at up to 1.0 GHz overall (Fig. 2(c)) [3].

Based on this experience, a next-generation detector with significant improvements in all elements from power supplies to ASICs to data acquisition is presently under development, with an expected completion date of late 2002. This will use 6 pairs of 128-channel ASICs (a newer high-energy preamplifier chip (CAFÉ-M) and a specially-designed buffer counter (BMC)), with optical coupling between detector and control/counting electronics to minimize noise and transients. The completion date for this project is estimated to be late 2002.

CONCLUSIONS

A prototype one-dimensional electron and photon detector operating linearly up to the GHz countrate level and with a resolution of 75 microns over 768 channels has been successfully developed and tested. An improved version of this detector is under development, with the same resolution and number of channels, but improved performance, programmability, and robustness in general user environments relative to the prototype. The next-generation detector should find use in several areas of synchrotron radiation research.

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[1] A.W. Kay, F.J. Garcia de Abajo, S.-H. Yang, E. Arenholz, B.S. Mun, N. Mannella, Z. Hussain, M.A. Van Hove, and C.S. Fadley, Phys. Rev. B 63, 115119 (2001); D. Nordlund, M.G. Garnier, N. Witkowski, R. Denecke, A. Nilsson, M. Nagasono, N. Martensson, A. Fohlisch, Phys. Rev. B 63, 121402 (2001); and abstract in the 2001 Compendium by N. Mannella et al.

[2] Local participants in the DetectorSync initiative include A. Thompson, H.A. Padmore, and C.S. Fadley, and the group's website is at--http://www-esg.lbl.gov/esg/meetings/detectorsync/index.html, with a more detailed white paper on detector needs also downloadable from this source.

[3] A.W. Kay, Ph.D. thesis (University of California, Davis, September, 2000), LBNL report 46885, and to be published.

[4] H. Kipnis, H. Spieler and T. Collins, A Bipolar Analog Front-End Integrated Circuit for the SDC Silicon Tracker, IEEE Trans. Nucl. Sci. NS-41/4 (1994) 1095-1103

[5] Ciocio et al., A Binary Readout System for Silicon Strip Detectors at the LHC, Proceedings of the First Workshop on Electronics for LHC Experiments, Lisbon, September 11-15, 1995, CERN/LHCC/95-56, 108-113

[6] . Albiol et al., Performance of the ATLAS Silicon Strip Modules, Nucl. Instr. and Meth. A403 (1998) 247-255.

[7] T. Dubbs et al., The Development of the CAFE-P/CAFE-M Bipolar Chips for the ATLAS Semiconductor Tracker, Proc. 5th Workshop on Electronics for the LHC Experiments (LEB 99), Snowmass, Colorado, 20-24 Sep 1999, 123-127.

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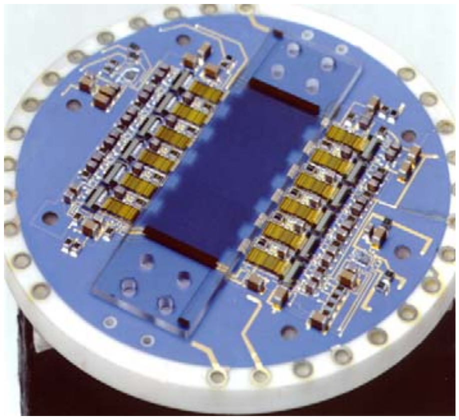
Principal investigator: Charles S. Fadley, Department of Physics UC Davis, and Materials Sciences Division, Lawrence Berkeley National Laboratory. Email: fadley@lbl.gov. Telephone: 510-486-5774

ALS GHz-RATE DETECTOR PROJECT

- **(a) Prototype:**
  - **768 channels (64 x 12 chip pairs)**
  - **Operation in real ALS environment**
  - **~75 micron spatial resolution**
  - **1 GHz overall linear countrate**
  - **demonstration of principle**



- **(b) Next generation:**
  - **768 channels (128 x 6 chip pairs)**
  - **~75 micron spatial resolution**
  - **>2 GHz overall linear countrate**
  - **spectral readout in as little as 60μs (time-resolved measurements)**
  - **programmable thresholds, readout format**
  - **more robust in all respects**
  - **size to fit current spectrometers**

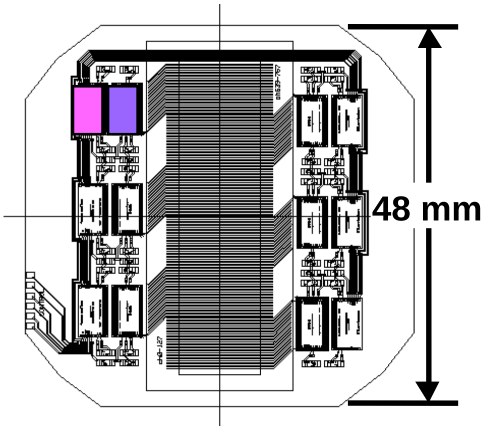


Figure 1--(a) Basic characteristics of the prototype GHz-rate detector developed as the first stage of this project, together with a photo of the ceramic substrate with 12 preamp-plus-counter chipsets mounted on it. The microchannel plates are not yet installed. (b) Basic characteristics of the next-generation detection now being designed and fabricated, together with a layour of its 6 chipsets and an indication of its size.

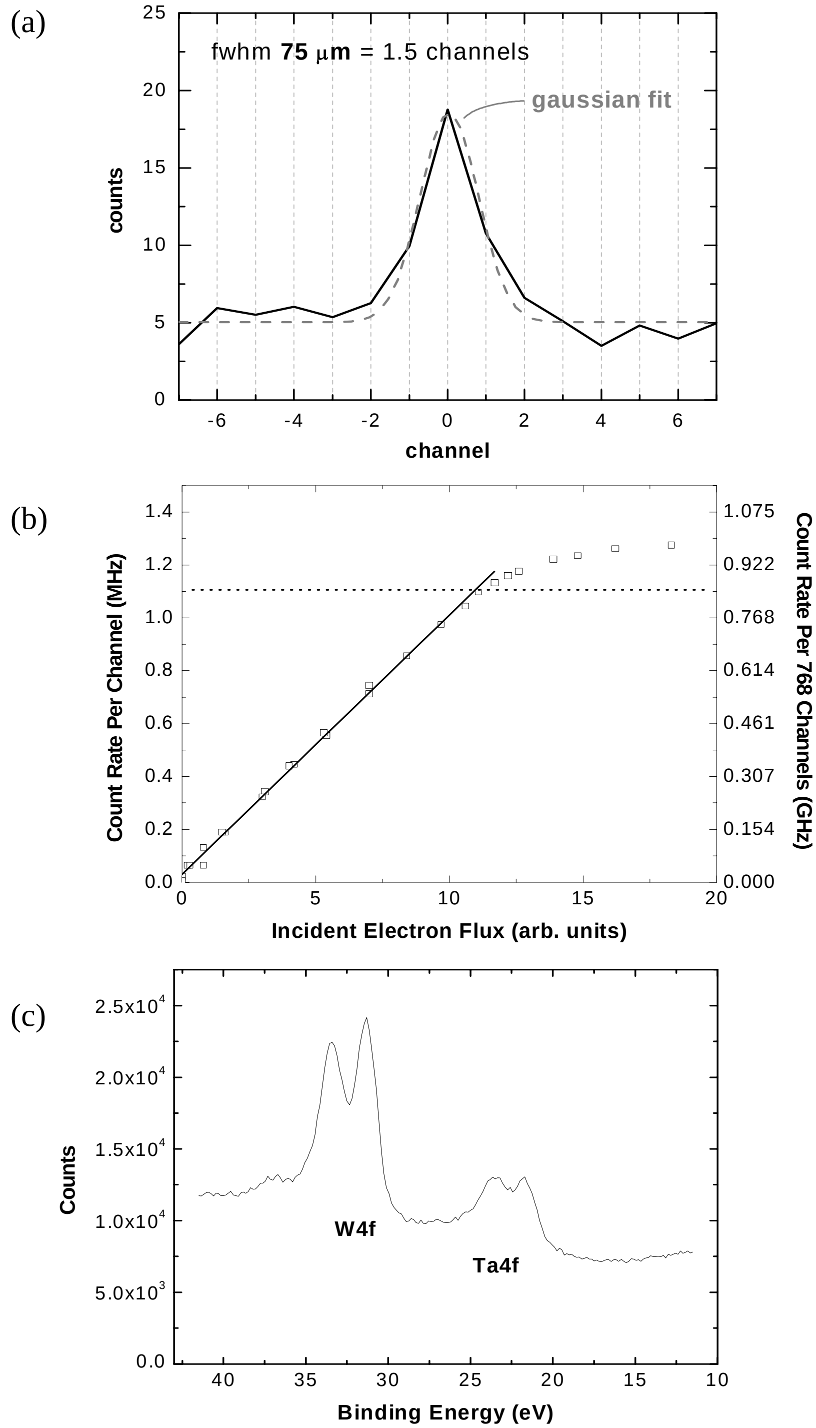


Figure 2--Test data from the first prototype detector shown in Fig. 1(a). (a) Spatial resolution determination via a collimated electron beam source. Each channel is 50 microns. (b) Counting linearity per channel (left scale) and over all channels (right scale) as determined with an electron gun. (c) Test spectra obtained with the detector mounted in a Scienta SES 200 spectrometer at ALS beamline 9.3.2.

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An ultrahigh-speed one-dimensional detector for use in synchrotron radiation spectroscopy: first photoemission results

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Abstract

We report on the design and construction of a next-generation, ultrahigh-speed, one-dimensional detector for electron and other spectroscopies, and discuss some first experimental results obtained with it. This detector is capable of recording spectra over 768 channels with ~1.5 channels (~75 μm) resolution and with good linearity up to countrates of >1 MHz per channel or >1 GHz overall. In first experiments with it, photoelectron spectra spanning several hundred channels of resolution have been obtained in as little as 50 ms; with future system improvements, this time should be reduced to 150 μs. The data obtained include rapid X-ray photoelectron diffraction scans and time-resolved core-level observations of a surface reaction process. This detector should open up several types of new experiment, including more rapid real-time observations of surface reaction kinetics by means of inner-shell spectroscopies.

Keywords: Time-resolved XPS; Fast XPD; Surface reactions; High-speed detector; Multichannel detector

1. Introduction

Developments in both laboratory X-ray sources and more importantly synchrotron radiation (SR) sources have led to astonishing increases over the last 20 years in the photon fluxes that can be delivered to a sample. However, there is a growing gap between what these sources can provide and what can be detected in the final experiment, especially when one considers third-generation SR sources, but even more so for the coming fourth-generation sources. At present, the brightness of third-generation synchrotron light sources often exceeds the capabilities of the end-station detector systems to adequately handle the electron or photon fluxes encountered in an experiment. This lack of sufficient detector capability thus often limits the types of experiments that can be performed.

An obvious example of one of the spectroscopies that could benefit significantly from advances in detector performance is inner-shell photoemission spectroscopy, often referred to simply as X-ray photoemission spectroscopy (XPS). This well-known technique provides element selectivity, quantitative analytical capability, distinction of chemical species by means of chemical shifts, more subtle magnetic and valence configuration information from multiplet-splitting and satellite structures, variable surface sensitivity (e.g. by changing electron exit angle or photon energy), and surface atomic structure information via photoelectron diffraction and holography. One recent addition to the capabilities of XPS is being able to carry out in situ time-resolved observations of surface structure and chemical reactions, and several pioneering observations of the latter type have already been performed [1–4]. Surface chemical reactions can occur with kinetic timescales over a very broad

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range from minutes to microseconds, depending on the particular reaction, the gas pressure above the surface and the temperature, and we cite as one example the mid-range timescale of ∼1 ms for the adsorption–desorption processes associated with some small molecules [5]. Thus, it is very desirable in the future to be able to obtain a spectrum in 1 ms or less in order to open up new time domains for such kinetics studies, as well as other types of time-resolved XPS studies. The timescale of conventional XPS measurements in which the spectrum is obtained by dithering the detector back and forth over a given energy window is several tens of seconds (e.g. as discussed in Refs. [1,2]), or, in snapshot mode with a fixed-energy-window position-sensitive detector and special readout electronics, it has been reduced to as little as 100 ms in conjunction with third-generation SR excitation [6]. Present detectors are also limited as to their highest countrates for both time-resolved and other types of spectroscopy, such as photoelectron diffraction measurements with angle variation. For several reasons then, a higher-speed multichannel detector capable of GHz overall rates, more rapid readouts, and several hundred channels is a very desirable next step.

As a first step toward further expanding time-resolved in situ observations of surface chemical reactions and surface structure and in general expanding the spectroscopic capabilities of third (and eventually fourth)-generation SR in several fields, we have designed and developed a new one-dimensional ultrahigh-speed detector for electron and other spectroscopies. This unique detector has 768 channels spaced by 48 μm, with an overall spatial resolution of about 1.5 channels (75 μm) and a maximum overall countrate of ∼1 GHz that is approximately 100× faster than any existing detector, and the ultimate ability as far as hardware is concerned to obtain a spectrum in as little as 150 μs. In this paper, we briefly review the basic design of the detector (with further details available elsewhere [7]) and concentrate here on some first experimental results obtained with it.

2. Basic detector design and construction

This detector is based on a first prototype that was assembled and tested about 3 years ago by Kay and coworkers [7a,8]. This prototype demonstrated the ability to operate in a real experimental situation in a Scienta SES-200 spectrometer, accumulating spectra in dithered mode and counting linearly up to about 1 GHz overall rate; however, this first version exhibited some problems with the custom-designed readout integrated circuit (IC), data transfer errors, and high-voltage breakdown. The basic design of the present detector, which is schematically shown in Fig. 1, is the same, but several improvements have been made: the preamplifier-discriminator IC has been replaced with a newer, higher performance, and more reliable IC (the 128-channel "CAFE-M" developed for high-energy physics tracking detectors [9]), and a new 128-channel deadtime-less, double-buffered counter and readout chip ("BMC") has been designed and implemented. A serial link is used to transfer spectra from the detector to the data acquisition system to minimize the number of ultrahigh-vacuum feedthroughs, and fiber optic links are employed in order to facilitate high-voltage isolation and

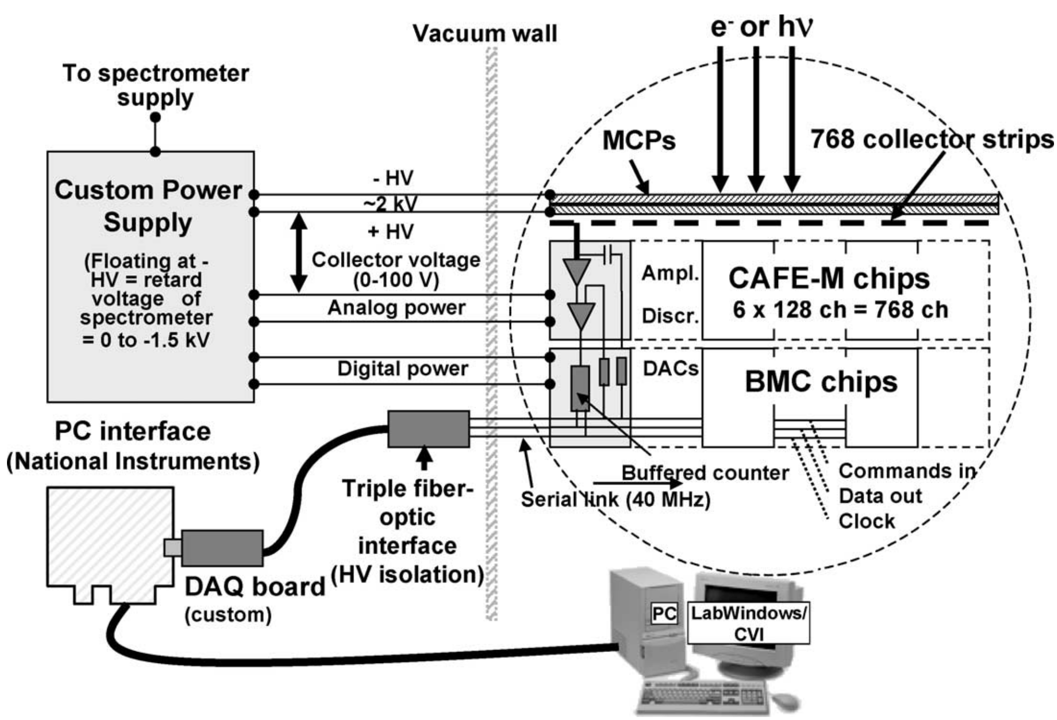

Fig. 1. Schematic view of the overall design of this high-speed detector, with various key components indicated.

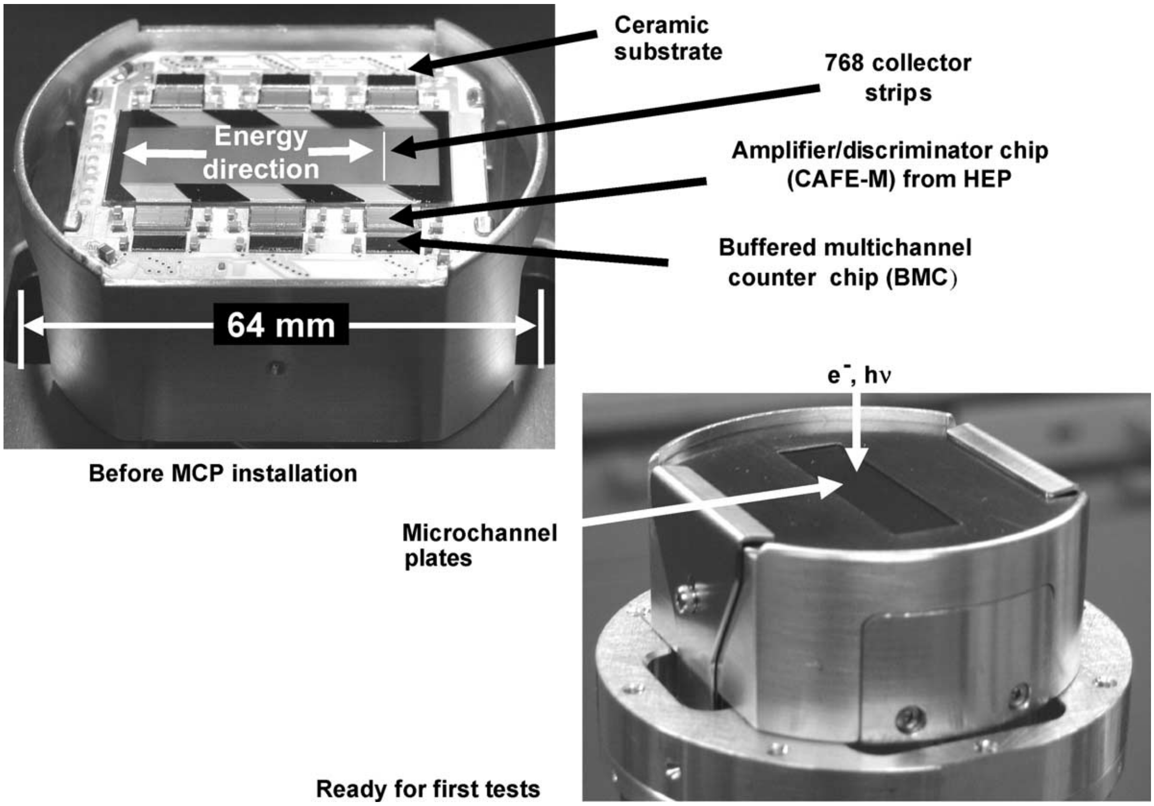

Fig. 2. Photos of the detector before installation of the microchannel plates and a protective top cover, and after installation of these components.

reduce noise pickup. High-voltage isolation has also been improved everywhere, and the mechanical size has been reduced to permit use in a variety of experimental systems. Fig. 2 shows two photographic views of the top end of the detector, with overall size indicated.

More detailed features of this detector are described elsewhere [7b], but its basic operation is as follows: electrons (or in other potential applications, soft X-ray photons) impinge on a pair of "hot" microchannel plates in a chevron configuration. The charge clouds emitted from the backside of the channel plate impinge on 768 linear gold collector strips with 48 μm spacing that are in turn wire bonded to six pairs of CAFE-M and BMC signal processing circuits. The CAFE-M has 128 channels of amplifiers and discriminators, with a pulse-pair resolution time of 50 ns that leads to a maximum *linear* countrate/channel of ∼2 MHz, or an overall countrate for all channels of 1.5 GHz. The input dynamic range is 1–10 fC (6000–60,000 e^-). The discriminator threshold is variable from 3125 to 31,250 e^-, and well above the noise level of about 1400 e^-. The CAFE-M is therefore suitable for the readout of microchannel plates operated at low gains of 10^4–10^5. This high input sensitivity is essential for high linear countrate operation since it is necessary to keep the current flow due to pulse generation at ≤1/10 of the normal "wall current" of the MCPs. Thus, a pair of "hot" microchannel plates, e.g. with a resistance per plate of ∼5 MΩ, can be operated at a gain of up to $\sim 10^5\,e^-$ for a 1.5 GHz linear countrate while maintaining a manageable power dissipation. Our detector also incorporates close-coupled water cooling to dissipate this heat.

The CAFE-M is followed by the BMC, which features a buffered counter for each channel, programmable control of threshold and calibration signals, and a serial link for the transfer of commands and data. The readout IC (BMC) can run at up to 40 MHz. The circuit contains two 24-bit counters for each of its 128 channels. The counters are connected in a double-buffered fashion for deadtime-less operation, so that new data may be acquired at the same time current data are being read out. The depth of the counters is programmable, with a maximum of 24 bits and a minimum of 4 bits, in order to provide the option of reducing the number of bits when a faster readout is required. The minimum readout time for 4 bits per channel is ∼150 μs with the current serial clock of 40 MHz. In the default mode of operation the time between two consecutive read operations is the integration time. In another mode of operation the integration time can be defined by "start counter" and "stop counter" commands. In this case, the time needed to send the "stop counter" command that defines the minimum integration time of 525 ns.

In preliminary tests of this detector and a first prototype which preceded it using an electron flood gun as a uniform excitation source, it has proven possible to count at up to ∼1.5 GHz over all 768 channels (Fig. 1(c) in Refs. [7a,7c]).

The detector has been installed in a Scienta SES-200 analyzer fitted with a custom-built carousel system that allows two detectors to be loaded in the vacuum simultaneously and swapped without breaking vacuum [8,10]. The overall system also includes water cooling, which is found to be essential to avoid the overheating of the circuits located in vacuum. The cooling system uses water at room temperature (20°–25 °C) and thus does not require a chiller. The detector can accept temperatures up to ∼120 °C, thus permitting it to operate after suitable bakeout in an ultrahigh vacuum environment at 10^{-10} Torr or less. Data acquisition is handled by means of PC-based hardware and software written in LabWindows/CVI [8].

Some special features of this detector as compared to an earlier multichannel version making use of custom-designed ICs [11] are: higher spatial resolution and thus energy resolution (48 μm collector pitch versus 470 μm pitch), higher overall countrate (∼1 GHz versus ∼10 MHz), more sensitive frontend ICs which permit operating the MCPs at lower gain, and more noise resistance due to having the ICs inside vacuum and close-coupled to the collectors, again permitting operation at lower overall MCP gains.

3. First experiments

All experiments were performed with the advanced photoelectron spectrometer/diffractometer (APSD) which is situated at the elliptically polarized undulator beamline 4.0.2 of the Berkeley Advanced Light Source [8,10]. Briefly, this experimental end station is equipped with facilities for LEED, ion bombardment, and normal XPS using a twin-anode Al/Mg X-ray tube, as well as the Scienta SES-200 spectrometer, the usual MCP + phosphor + CCD-based detector provided with this spectrometer, and our new high-speed detector. All photoemission measurements reported here were carried out with the new detector. The base pressure was 6.0×10^{-11} Torr during initial sample surface preparation and 4.0×10^{-10} Torr during actual SR experiments. A custom-built goniometer also permits rotating the sample under computer control over the full 360° range in azimuth and the meaningful range in theta above the sample surface. The measurements reported here were performed using both Al Kα radiation from the X-ray tube and undulator radiation. MnO(001) and Pt(111) single crystals were cleaned using established recipes including cycles of Ar sputtering, oxygen treatments, and UHV annealing at higher temperatures. Good surface cleanliness and atomic order were verified by a combination of XPS survey scans, X-ray photoelectron diffraction (XPD), and LEED.

4. Results and discussion

4.1. X-ray photoelectron diffraction (XPD) in seconds with a standard X-ray source

As a first demonstration of the rapid data acquisition possible with this detector, we have measured the azimuthal dependence of Mn 2p emission from a MnO(001) single crystal. In these experiments, the takeoff angle of the

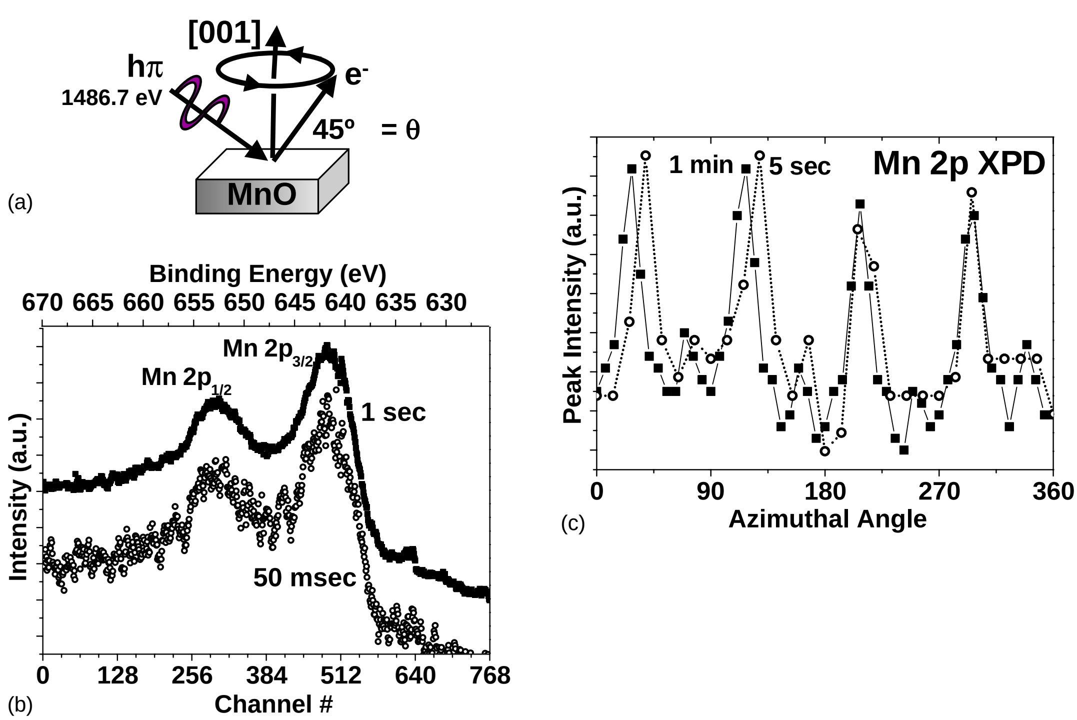

Fig. 3. (a) Experimental geometry for an X-ray photoelectron diffraction experiment based on Mn 2p emission at a takeoff angle of 45° from an MnO single crystal with (001) orientation. Al Kα radiation was used for excitation. (b) Mn 2p spectra taken with the high-speed detector in snapshot mode, with the detector held open for counting over 1 s and 50 ms. (c) Azimuthal dependence of Mn 2p XPD patterns obtained over full scan times of 1 min and 5 s. The maximum and minimum intensities of the peaks have been normalized to have the same value for this plot.

emitted electrons with respect to the surface was 45°, and a non-monochromatized Al Kα X-ray tube was used for excitation. The experimental geometry is shown in Fig. 3a.

The data presented here were taken with the external control and data handling for the detector in a partially completed "demonstration" state that has already been improved. Specifically, one computer was used to control the data acquisition, while another was used for the spectrometer, without any time synchronization between them. In one demonstration experiment, the sample was set in azimuthal rotation by one computer and, just after the beginning of the movement, the second computer was set to take snapshot spectra in short time intervals of every 1.0 s or every 50 ms, depending on the setup parameters. The actual setup of the detector data acquisition uses a software timer to manage both the integration time and the interval between spectra. Because of that, there is a limitation due to the underlying operating system on the fastest timing that can be used. Future improvements will permit handling the synchronization in hardware in order to achieve the fastest operation permitted by the 150 μs minimum readout time.

Fig. 3(b) shows Mn 2p XP spectra taken in snapshot mode and with the detector counting over time windows of 1 s and 50 ms. Such spectra were then taken during a full 360° azimuthal scan, and the intensity of the Mn 2p peaks subsequently plotted as a function of azimuthal angle, as shown in Fig. 3(c). With a fixed azimuthal rotation speed, spectrum acquisition times can be directly converted to angular positions. Full scans were in this case obtained in a total of 1 min and 5 s, respectively, yielding the two curves overlaid in Fig. 3(c).

The four-fold symmetry of the MnO(001) surface is clear in both of these XPD scans. But beyond this, the 1 min pattern shows additional fine structure in between the strongest four peaks spaced 90° apart. The quality of this level of time-resolved XPD data is thus good enough

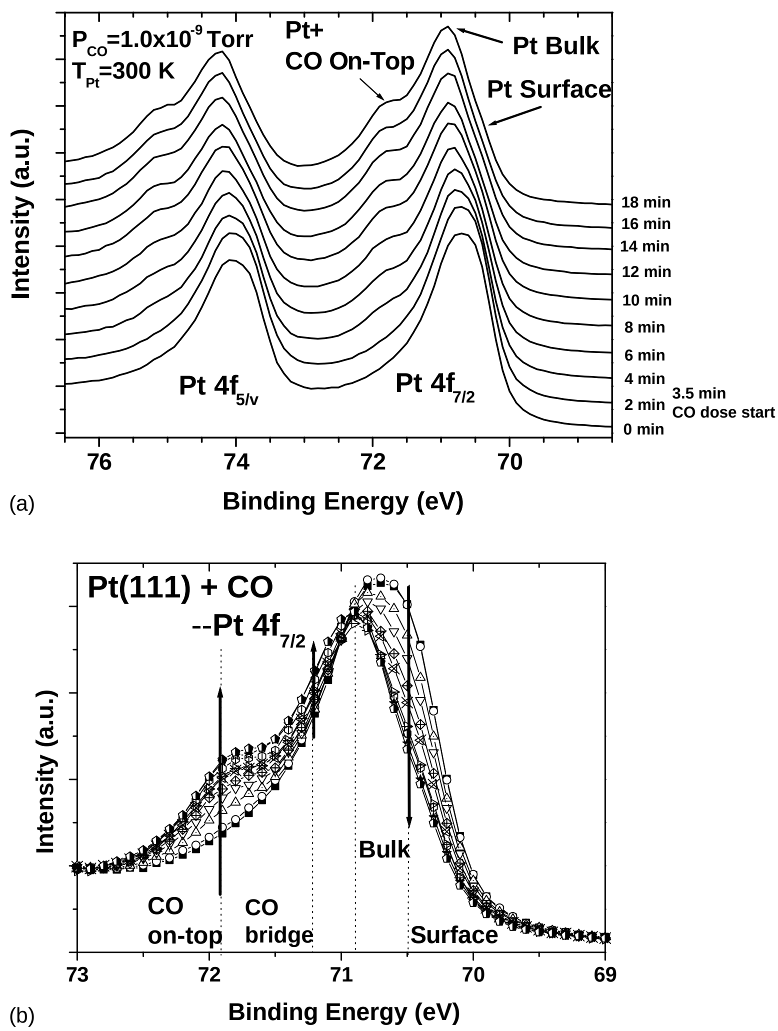

Fig. 4. (a) Evolution of the Pt 4f spectrum from Pt(111) as a function of CO exposure at a pressure of 1×10^{-9} Torr, and (b) overlapping Pt $4f_{7/2}$ spectral regions taken from the data in (a) and more clearly showing the evolution of surface core-level shifts. The binding energies of the four peaks expected are [12]: Pt surface = 70.5 eV; Pt bulk = 70.9 eV; Pt with bridge-bonded CO = 71.2 eV; and Pt with on-top CO = 71.91 eV. At the first stage (0 to ∼10 min), the surface component decreases, and at the same time the CO on-top component increases. Thereafter (from ∼12 min), the CO bridge component begins to decrease.

for more detailed analysis so as to determine surface structural information. Even the 5 s pattern retains most of the fine structure, although of course the statistical scatter of the points is higher. These data thus represent a capability for carrying out XPD measurements that is roughly 100× faster than has been possible previously.

4.2. Time-resolved XPS of a surface reaction with synchrotron radiation

We have also performed high-speed XPS experiments in a time-resolved mode so as to follow a surface chemical reaction. The element and chemical-state specificity of high-resolution core-level XPS is a powerful advantage, as compared, for example, to surface sensitive vibrational spectroscopies such as infrared absorption spectroscopy (IRAS) and electron energy loss spectroscopy (EELS). These measurements used third-generation synchrotron radiation for excitation, as described above. The reaction we have studied is the transition from clean Pt(111) to Pt(111) with an adsorbed layer of CO. This system exhibits chemical shifts between C and O atoms in on-top and bridge adsorption sites, as well as surface core-level shifts (SCLSs) between clean surface and bulk Pt atoms, and between Pt atoms with on-top and bridge CO adsorption [12] and has been the object of study in prior time-resolved XPS experiments [1,3,4]. As a first illustration of our data, Fig. 4(a) and (b) shows the evolution of the Pt 4f SCLSs as a function of CO exposure at a substrate temperature of 300 K, using a 380 eV photon energy. Each spectrum was taken over a counting time of 1 min, with a spacing of 2 min, while the sample was exposed to an ambient pressure of 1×10^{-9} Torr of CO. The spectra indicated as 0 s corresponds to clean Pt(111). It is obvious that, as the exposure of CO is increased, the higher binding energy components increase, while the lower-binding-energy components increase. Prior work [1,3,4,12] has shown that the higher-binding-energy component corresponds to the signal from surface Pt atoms, and the lower-binding-energy side contains signals from Pt with bridge and on-top adsorbed CO. Our data show that not only signals from surface Pt with on-top CO, but also signals from surface Pt with bridge CO, located just to the lower binding energy side of bulk Pt, are observed in the higher-exposure spectra.

In a first attempt to study faster surface processes, the CO pressure was raised to 1×10^{-8} Torr. Although the overall timescale of this surface reaction is still long compared to the minimum counting time of our detector, the same sort of Pt 4f experiment was performed again in a snapshot mode and with a counting time of only 50 ms. With a delay between spectra of about 450 ms due to software overhead that will be eliminated with future improvements in progress, over 3000 spectra were thus obtained over a time of ∼23 min. Fig. 5a

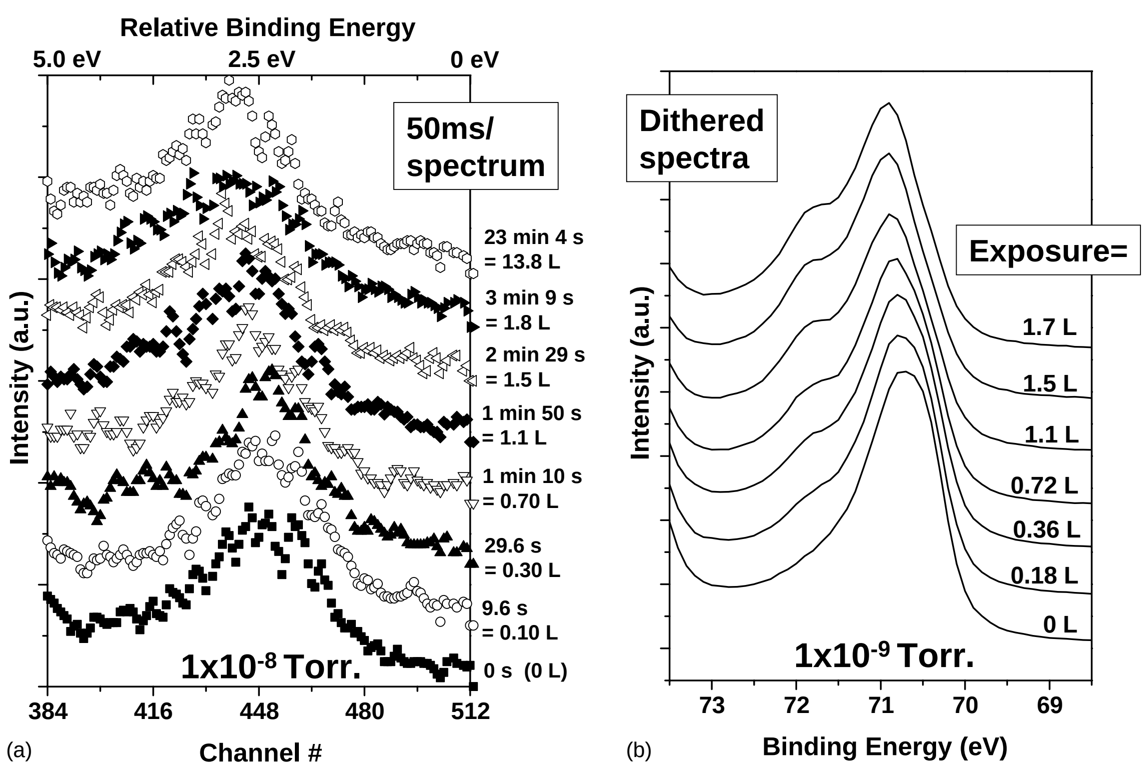

Fig. 5. (a) Evolution of Pt 4f spectra with time at a CO pressure of 1×10^{-8} Torr, with each spectrum representing counts accumulated in a 50 ms time window. (b) Time-averaged dithered Pt 4f spectra obtained with a lower CO pressure of 1×10^{-9} Torr, and selected to correspond to the same exposures in Langmuirs as the data in (a), although the latter end at a higher limit. Although the statistical accuracy in the 50 ms spectra does not permit clearly resolving features, the general spectral shapes follow those of the better resolved dithered spectra, that is, spectral weight shifts toward higher binding energies, and a shoulder grows in on the high-binding-energy side.

shows eight individual 50 ms spectra selected from among these 3000. For comparison, Fig. 5b shows seven dithered spectra obtained in another exposure sequence at a lower pressure of 1×10^{-9} Torr, with longer times being chosen to correspond to most of the exposures in Langmuir (L) of the 50 ms spectra. The 50 ms spectra do not have adequate statistical accuracy to unambiguously see fine structure, but comparing them with the dithered spectra shows very similar changes in overall spectral shape. In particular, both sets of spectra show spectral weight shifting toward the higher binding energy side as time progresses. Thus, these data demonstrate that large data sets of several hundred channels in each spectrum can be accumulated with as little as 50 ms counting times.

5. Conclusions and future prospects

In this short paper, we have presented some first experimental results from an ultrahigh-speed multichannel detector for electron and other spectroscopies. This detector features 768 channels with a spatial resolution of ~1.5 channels (~75 μm) and an overall countrate capability of ~1 GHz. We have here demonstrated the ability to count over 50 ms in obtaining photoelectron diffraction and carrying out time-resolved core-level reaction spectroscopy. However, the basic detector electronics already would permit higher-speed operation, with the current limiting factors being the data acquisition system and the software-controlled timing. Improvements of the system currently underway (for example, inboard memory in the interface board) will allow us to take full advantage of the high-speed characteristics of the detector, leading to minimum counting times of 150 μs. With such spectral speeds and perhaps also pump-probe-type experiments using rapid valves or laser excitation, it should be possible to signal average over spectra at various delay times, thus improving statistics and permitting a wide variety of surface reaction kinetics to be studied. Beyond this, pumping magnetic materials with short field pulses is another type of pump-probe experiment that should permit studying spin relaxation dynamics.

Another interesting aspect of this detector is its MCP-based front-end architecture, which permits counting electrons as well as soft X-ray photons with a suitable front end photocathode coating. Thus, it should also be possible to apply it to other electron spectroscopies (e.g. valence photoemission, electron energy loss spectroscopy, etc.), as well as soft X-ray-based experiments (X-ray emission spectroscopy or time-resolved X-ray absorption spectroscopy [13]). With further development to add front end coatings sensitive to visible and IR radiation (probably requiring encapsulation due to the extreme surface sensitivity of the coatings), this detector could also find use in laser spectroscopy.

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An Ultra-High-Speed Detector for Synchrotron Radiation Research

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Abstract. An ultra high-speed, one-dimensional multi-channel detector for electrons and soft x-ray photons has been developed to permit full utilization of fluxes from third- and fourth-generation synchrotron radiation sources. The detector has 768 channels of buffered counters with a maximum linear countrate per channel exceeding 2 MHz. With an overall countrate of ~2 GHz, this detector is approximately 100 times faster than any other presently available. The 48 μm spacing from channel to channel also provides excellent spatial resolution, and thus also excellent energy resolution with dispersive spectrometers. This detector represents several improvements in reliability and ruggedness over an earlier prototype. The detector is capable of operating in a typical UHV environment and is presently installed in a Scienta electron analyzer at the ALS for testing and first data taking. A total countrate exceeding 1 GHz and a position resolution of about two channels have been experimentally demonstrated. It should be possible to read out all 768 channels in as little as 100 μs for time-resolved and pump-probe experiments.

INTRODUCTION

Too often the brightness of third-generation synchrotron light sources exceeds the capabilities of the end-station detector systems to adequately handle the electron or photon fluxes encountered in an experiment. This problem will be even worse with the advent of the fourth generation. As a first step toward relieving this bottleneck, we have developed an ultra-high-speed (~2 GHz maximum total countrate), one-dimensional detector array for electrons. This detector should also be useful for vuv/soft x-ray photons. This device is capable of handling the highest countrates encountered in electron spectroscopy to date, thus permitting the fullest utilization of the radiation, as well as new kinds of time-resolved experiments. Such new experiments could include time-resolved photoemission, soft x-ray resonant magnetic scattering & x-ray emission spectroscopy; and real-time energy-dispersive transmission x-ray absorption spectroscopy. The detector is also free from non-linearity problems that have plagued CCD detectors in the past [1], and pushes the upper end of linear counting upward by a factor of approximately 100.

This project has made extensive use of detector technology developed for high-energy physics (HEP). With a chevron microchannel-plate (MCP) as the first amplification stage, custom-designed integrated circuits (ICs) are used for the multichannel preamplification, discrimination, and counting that is required. The CAFE-M chip [2], originally developed for the ATLAS SCT detector, serves as the analog front-end. This IC is followed by a custom-designed buffered multichannel counter (BMC) chip for deadtime-less readout.

The detector described here follows a first prototype [3] which had already demonstrated the ability to count linearly at up to 1.0 GHz overall, and a spatial resolution of 75 μm FWHM. The new version features several significant improvements: a much more robust design, an increased countrate capability, a reduced size to fit existing spectrometers, and a faster readout.

DETECTOR DESIGN

Electrons are detected and counted by a state-of-the-art configuration of microchannel plates, a finely spaced array of charge collection electrodes, and custom-designed integrated circuits, as schematically shown in Fig. 1. The electrons impinge on a pair of "hot" microchannel plates in a chevron configuration. The active counting area is 38.4 mm by 10 mm. The charge clouds emitted from the backside of the channel plate impinge on 768 collector strips with 48 μm spacing that are wire bonded to 6 pairs of signal processing ICs. Each front-end IC (the CAFE-M, a proven device from high energy physics) has 128 channels of amplifiers (peaking time 25 ns) and discriminators. The pulse-pair resolution time is 50 ns, leading to a maximum linear countrate/channel of ~2 MHz. The front-end IC is followed by a custom-designed buffered multichannel counter (BMC) IC permitting a deadtime-less readout. The BMC IC features a buffered counter for each channel, programmable control of front-end gain, threshold and calibration signals, and a serial link for the transfer of commands and data. The depth of the counters is programmable, with a maximum of 24 bits, in order to provide the option of reducing the number of bits when a faster readout is required. The minimum readout time for 4 bits/channel is ~ 80 μs.

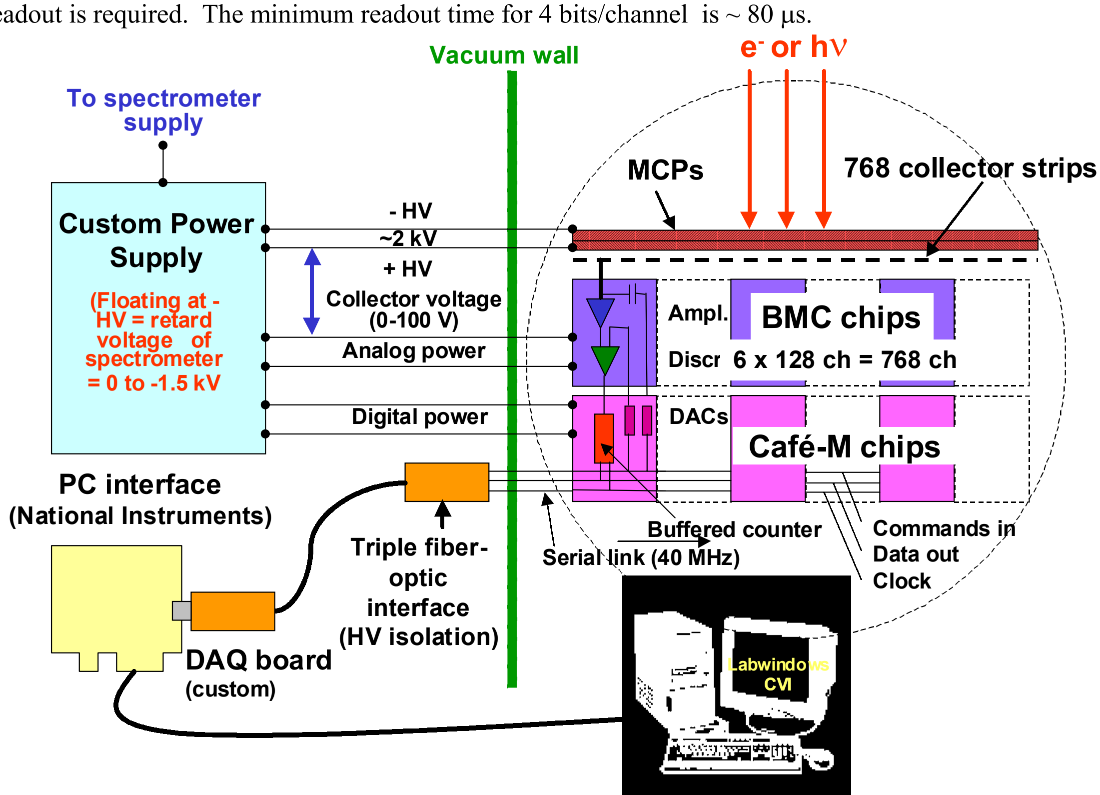

Figure 1. Ultra-high-speed detector system schematic

The detector can float at high potential with respect to ground if needed, in particular at the retarding potential of an electron spectrometer. This float potential can be up to 3 kV; with some special additional insulation, going up to 10 kV should be possible. In order to avoid high voltage damage to ICs and other components, as well as unwanted noise via ground loops, the serial command and data lines are connected to the data acquisition system via three optical fibers through an optical interface board. The detector is thus protected against high voltage failures such as a short from detector common to ground. A field-programmable gate array (FPGA) based interface residing on the PC-side of the opto-interface board serializes and parallelizes the commands and readout data, respectively. A National Instruments digital input/output board (PCI-DIO-32HS) is used as the PC interface. The system is operated with LabWindows/CVI-based software.

As seen in Figure 2, the active elements of the detector are assembled on a ceramic substrate. Wire-bonds connect collector strips and ICs. This assembly is finally surrounded by a protective shell. The ceramic substrate is attached to a water-cooled aluminum block using alternating Kapton and tin foils to achieve good thermal conductivity while maintaining sufficient electrical isolation. The MCPs are held in place by a spring-loaded top cover plate. Presently a pair of matched MCPs with a 12 μm channel diameter (Photonis, France) is used in a chevron configuration. Lower-resistance "hotter" MCPs should permit even faster counting.

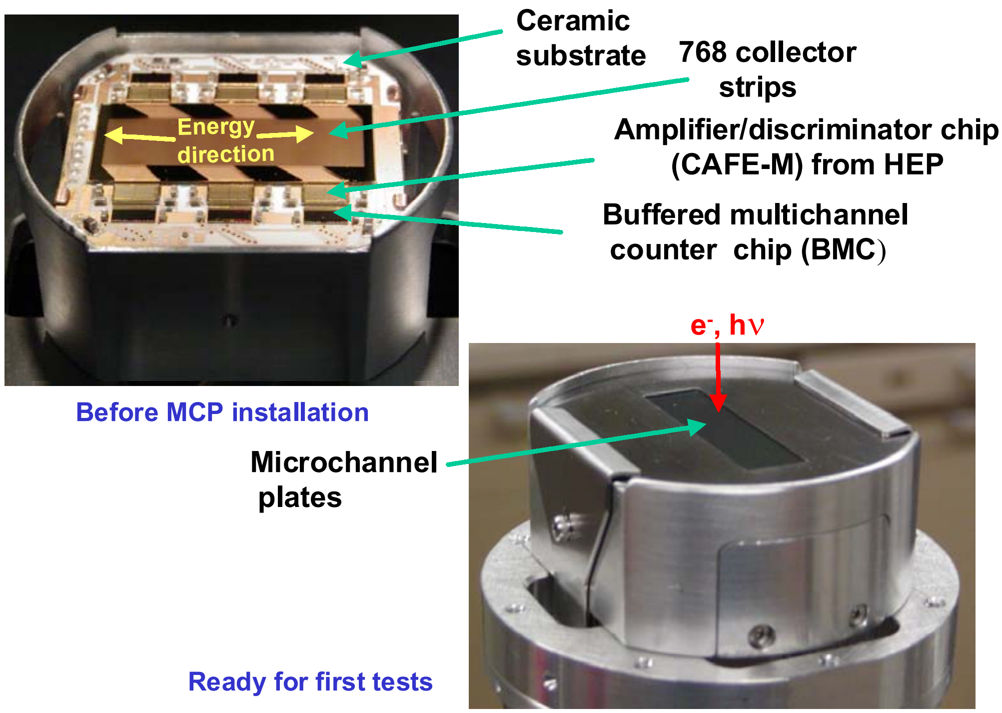

Figure 2. Detector assembly

DETECTOR PERFORMANCE

The detector is bakeable to 100 degree Celsius and thus capable of operating in a typical UHV environment. It is presently installed in a Scienta SES200 electron analyzer at EPU beamline 4.0.2 of the Advanced Light Source for testing and first data taking. The detector has been operated at a total countrate exceeding 1 GHz. The dark countrate (no electron exposure) is negligible. The spatial resolution has been tested with a special VUV lamp setup, as depicted in Fig. 3. Light the UV-lamp is collimated by a pair of slits in front of the detector to ~ 50 µm on the MCP. The measured countrate distribution across the exposed channels shown in Fig. 3(b) and demonstrates a spatial resolution of 2.5 channels or ~ 120 µm FWHM. This value is somewhat larger than expected, is most likely attributable to slit alignment inaccuracies, and should be regarded as an upper limit.

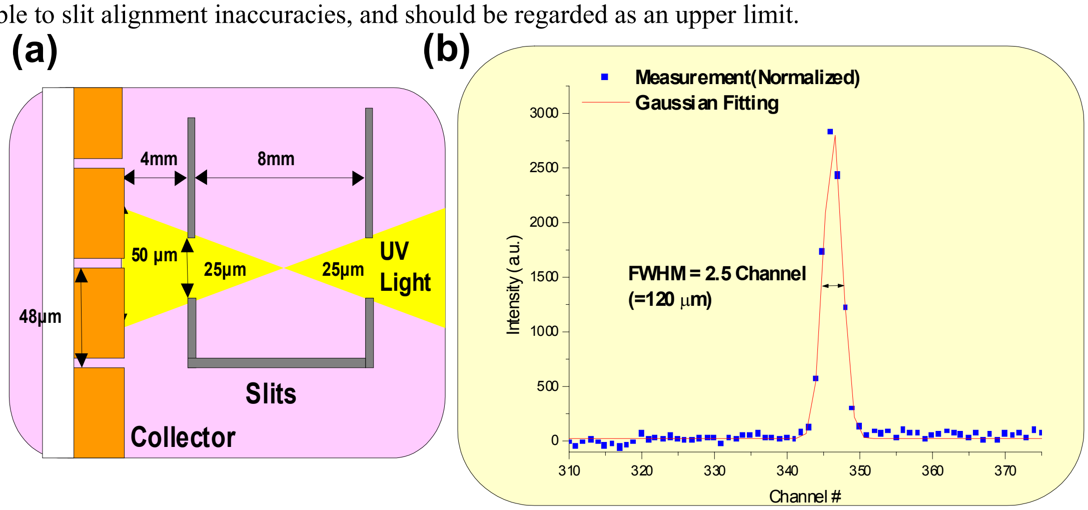

Figure 3. Test of spatial resolution. a) two slit test geometry, b) measured countrate distribution.

As a first illustration of the type of data that has been taken with this detector, we show below two azimuthal photoelectron diffraction scans for Mn 2p emission from an MnO single crystal. One scan was made in one minute, and the other in only 5 seconds. Thus, rapid scanning of photoelectron angular distributions is possible.

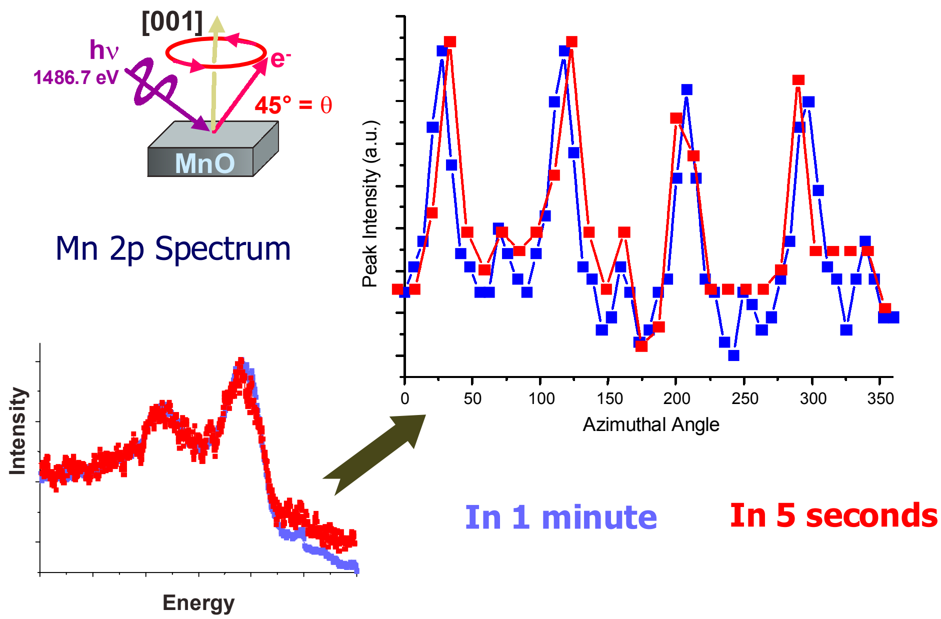

Figure 4. Some first photoelectron diffraction data obtained with this high-speed detector.

For time-resolved studies the detector can be read out in less than 100 µs at the current 40 MHz operation. However, the readout electronics has been designed to operate up to 100 MHz, with correspondingly shorter readout times. The overall diameter of the detector as shown at right in Fig. 2 is less than 65 mm, and thus should fit into a variety of current electron spectrometers or other experimental systems. The use of the detector could be greatly expanded by depositing a suitable photocathode material on the front of the MCPs for the detection of vuv/soft x-ray photons. This would open up important applications in, for example, real-time, energy-dispersive, transmission x-ray absorption spectroscopy. In addition, if equipped with a visible light/IR photocathode such a detector should find use in the related field of laser spectroscopy.

ACKNOWLEDGEMENTS

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A Next Generation, High Speed Detector for Synchrotron Radiation Research

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***Abstract*—A high-speed, one-dimensional detector array for electrons and UV/X-ray photons has been developed. The detector is capable of handling the high countrates encountered in at third generation synchrotron radiation sources and is free from nonlinearity problems present in charge coupled device (CCD) detectors. Electrons are counted by a configuration of microchannel plates, an array of charge collection electrodes, and custom-designed integrated circuits (IC) assembled on a ceramic hybrid. The charges are collected on 768 strips with a 48 μm pitch that are wire-bonded to 6 pairs of signal processing ICs. Each front-end IC has 128 channels of amplifiers (peaking time 25 ns) and discriminators. The pulse-pair resolution is 50 ns leading to a maximum linear countrate/channel of 2 MHz. The second, custom-designed IC features 24-b buffered counters and a serial link for the transfer of commands and data. A possible deadtime-less readout of all channels in 150 μs opens the door to time resolved experiments. The complete detector system includes the high-voltage power supply, a field programmable gate array (FPGA)-based data acquisition system, and supporting software. Special care has been taken to insure reliable operation in an ultra-high vacuum environment. The detector architecture and design is described and measured performance characteristics such as spatial resolution and count-rate linearity are presented.**

***Index Terms*—Detector, electron spectroscopy, high-speed, integrated circuit, one-dimensional, multichannel plate (MCP).**

I. Introduction

Developments in both laboratory X-ray sources and more importantly synchrotron radiation (SR) sources have led to astonishing increases over the last 20 years in the photon fluxes that can be delivered to a sample. However, there is a growing gap between what these sources can provide and what can be detected in the final experiment, especially when one considers third-generation SR sources, but even more for the coming fourth-generation sources. At present, the brightness of third-generation synchrotron light sources often exceeds the capabilities of the end-station detector systems to adequately handle the electron or photon fluxes encountered in an experiment. Severe nonlinearity effects often begin to appear at an overall countrates of 1–10 MHz [1], [2], [5]. Few systems are able to perform in multichannel mode at higher than about 50 MHz overall countrates. Beyond this is the necessity for each channel in the detector to be sufficiently narrow in atleast one spatial dimension such that adequate energy resolution can be achieved. Thus, in many cases, this lack of sufficient detector capability limits the types of experiments that can be performed.

X-ray photoelectron spectroscopy (XPS) is a type of experiment that can benefit from an improved detector system. Its variable surface sensitivity to the beam energy and incident angle allow the reconstruction of the surface atomic structure information using photoelectron diffraction and holography. This type of experiment requires a large amount of time to be performed ($\sim$ 2 hours per photoelectron diffraction spectrum—a photoelectron diffraction spectrum being the result of an angular scan of the sample surface while recording XPS spectra) and would greatly benefit from a fast detector. A conventional XPS spectrum is obtained in several tens of seconds. This is because maintaining a good energy resolution with the limited number of available channels on current detectors requires the spectrum to be dithered. Thus, XPS would substantially gain from a detector having a large number of channels and a good spatial resolution. Excellent linearity at high countrates is also highly desirable.

Another benefit of having a fast detector is the exciting capability of doing time-resolved XPS. This would allow the observation of surface structure changes as well as chemical reactions. The latter can span timescales from minutes to microseconds depending on the type of reaction. Previous work [3] set the limit as low as 100 ms/XPS spectrum.

Many experiments at synchrotron radiation light sources would be greatly helped or made possible by a high-speed detector with several hundred channels and an overall countrate in the gigahertz range and sub-millisecond readout.

II. Detector Description

A. Experimental Setup

The detector primary design consideration was to be a plug-in replacement for the detection system used in an electron spectrometer made by Scienta (SES200) at beamline 4 of the ad-

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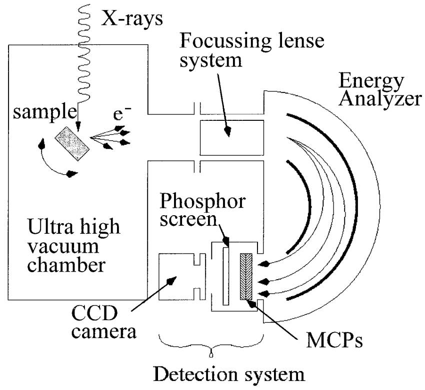

Fig. 1. Simplified block diagram of the experiment installed at the beamline 4 of the ALS showing the location of the original electron detection system.

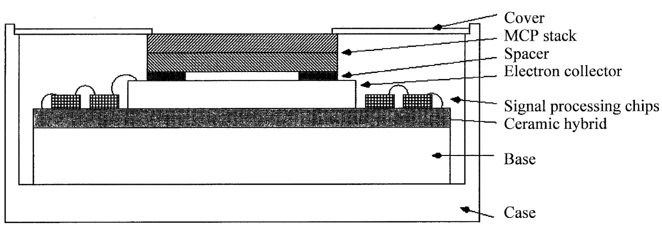

Fig. 2. Cross-section of the high-speed detector. The drawing is not to scale.

vanced light source (ALS) at the Lawrence Berkeley National Laboratory. Fig. 1 describes the experimental setup.

The sample being analyzed can be oriented in any direction. It can be heated or cooled. It is also possible to apply either a voltage or a magnetic field to the sample. Incident X-rays trigger the emission of photoelectrons of which the kinetic energy is measured by the hemispheric analyzer and the position sensitive detector.

B. High-Speed Detector Architecture

The new high-speed detector has been designed to replace the assembly composed of the multichannel plate (MCP) pair, the phosphor screen and the charge coupled device (CCD) camera. A first prototype [4] demonstrated the feasibility of the new detector but encountered many system-related issues. The new version described thereafter is based on the same architecture (Fig. 2) but uses improved components and eliminates previous design shortcomings. This is a one-dimensional (1-D) detector. The implementation is similar to the one described in [5] with the main difference that most of the signal processing electronics is located in the vacuum chamber thus reducing the number of feedtroughs and allowing a greater number of channels.

1) MCP: The high-speed detector uses a stack of MCP like the original detection system. They are used to multiply the number of the electrons being detected and improve the signal to noise ratio. So-called "Hot" MCPs are used to make sure that they will be able to handle a high countrate without saturation. The two plates are arranged in a chevron configuration to achieve a high gain and to prevent back scattering. The MCPs are from Photonis and their main caracteristics are listed on Table I.

TABLE I
MCP CARACTERISTICS

Parameter	Value
Gain	~1000
Operating voltage	1 kV
Hole diameter	12 µm
Thickness	0.6 mm
Resistance	~20 MΩ

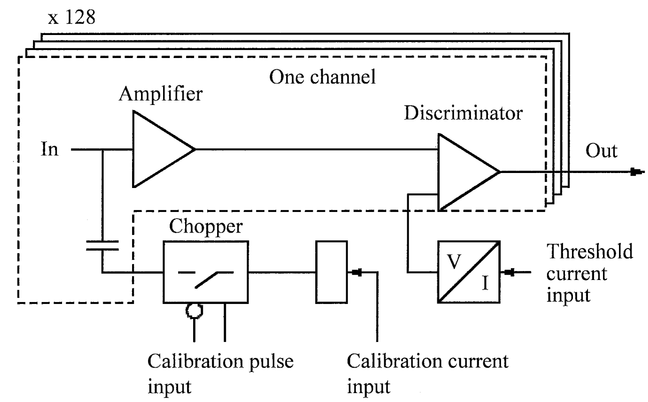

Fig. 3. Block diagram of the CAFE-M chip. For clarity, the bias and reference generator block that is common to all 128 channels has been omitted.

2) MCP Connections and Spacer: The MCPs were purchased (Photonis, France) as matched pairs to allow stacking without requiring a resistor network to evenly divide the voltage between the two plates. This makes the mechanical assembly simpler since only two connections are needed. The front connection is done by the stainless steel cover that holds the MCP stack in place.

The back connection is made with a 50 μm thick kapton spacer with a gold metallization on one side. The kapton is cut to form a four-finger grid in order to minimize the dead areas (where electrons will not reach the collector).

3) Collector: The collector is made of a 0.5-mm glass plate with a Cr-Au metallization. The size is 18×40 mm with an active area (electron collection area) of 10×40 mm. This latter has been chosen to match the sensitive area of the CCD-based detection system. The 768 collector strips are 30-μm wide on a 48 μm pitch.

4) Signal Processing Chips: The signal processing is done by two custom integrated circuits (ICs). The first one, the CAFE-M takes care of the analog processing while the second one, the buffered multichannel counter (BMC) does the pulse counting and manages the readout functions of the detector

a) CAFE-M: The CAFE-M [6] is a prototype readout chip designed for the readout of the ATLAS semiconductor tracker (SCT). It is made in a complementary bipolar process from MAXIM Semiconductors.

Fig. 3 presents a simplified block diagram of the chip and Table II lists its main characteristics. It includes 128 channels of amplifier and discriminator.

The collector of the input transistor is adjustable via an external resistor. The circuit is used in its typical configuration with a bias current of 300 μA. The two extremes of the power

TABLE II
CAFE-M CARACTERISTICS

Parameter	Value
Gain at the comparator	100 mV/fC
Peaking Time	25 ns
Output Amplitude	100 μA
Double Pulse Resolution (Q=4 fC)	50 ns
Time Walk (Q=1.25-10 fC)	< 15 ns
Supply Voltage	3.5 V
Power Dissipation	1.2-1.8 mW

dissipation indicated on Table II correspond respectively to a bias current of 150 and 300 μA.

The dynamic range of the CAFE-M is 1 to 10 fC. Simulated in the conditions of a normal configuration for the ATLAS SCT detector: 18-pF detector capacitance and 2-nA detector leakage current, the noise level is less than 1400 electrons. In the case of the high-speed detector, the noise is much lower because the input capacitance is smaller (detector: 20 fF + chip bond-pad capacitance: $\sim$ 0.5 pF). Noise is not an issue since the MCP stack provide an amplification of up to $\sim 10^6$.

The CAFE-M features a calibration circuit which groups the channels in four interleaved blocks with 32 channels pulsed at the same time. This allows threshold monitoring and internal cross-talk measurements.

The threshold control circuit is common to all channels with a 4% channel to channel matching.

All control signals and the outputs operate in current mode to minimize noise susceptibility and generation.

Each channel in the CAFE-M is able to resolve two pulses separated by 50 ns. Thus, pulses arriving in a periodic train with this spacing, or at 20 MHz, could be counted linearly. However, true counting pulses will be randomly spaced in time, so that avoiding pulse overlap finally gives a maximum linear counting frequency of about 2 MHz/channel assuming an arbitrary safety factor of 10 to reduce pulse pile-up. This limitation is not always clearly recognized in stating the linearity range of detection systems.

b) BMC: The BMC is a circuit that has been designed specifically for the high-speed detector as a companion chip for the CAFE-M. It has been fabricated in the 0.35 μm complimentary metal-oxide semiconductor (CMOS) process of Taiwan Semiconductors (TSMC). Fig. 4 shows its block diagram.

The BMC [7] contains 128 double-buffered counters to allow deadtime-less readout. Automatically switched by a read request one counter is counting, while the other can be read. The minimum integration window is limited by the time needed to read the detector since the read operation of one counter bank has to be finished before a new read is requested. The 24-bit counters can be configured to use 4, 8, 12, 16, or 24 b in order to speed-up the readout. The BMC also includes the services needed to operate the CAFE-M and several configuration registers. A mask register allows individual channels to be enabled or disabled (hot channel suppression). In addition to sending a signal to the input of the CAFE-M, it is possible to send a pulse directly to the input of a counter. This improves the testability of the detector before and after its installation in the electron-analyzer.

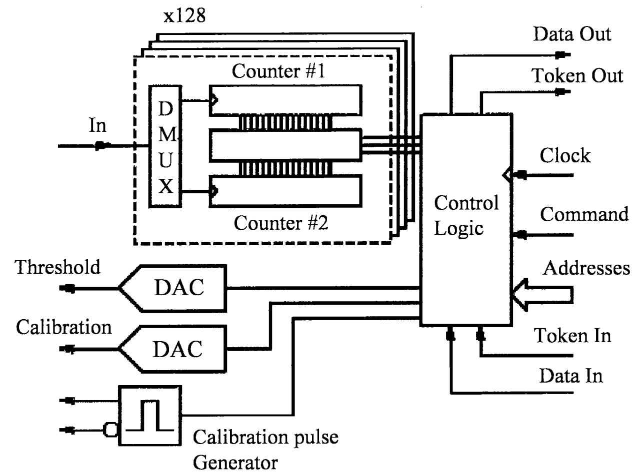

Fig. 4. BMC block diagram.

Each counter has a current to voltage converter at its input to accept the current mode output of the CAFE-M. The converter uses low and high level reference currents coming from the CAFE-M. This configuration ensures automatic tracking of changes (temperature, aging, process variation) in the CAFE-M. Two 8-b potentiometric digital to analog converters (DACs) are used to generate the threshold and calibration currents. Again, the DACs use a reference current provided by the CAFE-M. This way, the generation of the calibration and threshold current is independent of the process variations in the BMC.

The BMC uses a serial link to communicate with the data acquisition (DAQ) system because the detector is located inside the vacuum chamber and the number of feedthrough is limited. The implementation is based on a synchronous link using three wires and a very simple protocol.

The three wires are: clock, command and data. The **clock** is used to synchronize all transfers. The BMC has been designed to allow the clock to be turned off to reduce pick-up noise. **Command** is the line that is used to configure and control the operation of the BMC. **Data** carries the response of the BMC to the commands that are sent (e.g., the content of the counters).

Clock and command are fed in parallel to all BMC while data is wired in a daisy chain fashion. This latter choice facilitates the readout but could be reconsidered if there were a need to improve the reliability of the detector. The BMC uses a token-passing system to synchronize the data readout between the chips.

A 4-b geographical address allows individual access to a BMC chip. Up to 15 chips can be used together. One address (the 16th) has been reserved as a broadcast address. This speeds-up the communication when the same command has to be sent concurrently to all chips.

The protocol used for the communication organizes the data transfers in frames. Each frame starts with a 4-b header used for synchronization. It is followed by a 4-b address that represents the target BMC in the case of a command or that identifies the sender in the case of a reply. Then comes either a 5-b field that contains the command to be executed or a data type identifier in the case of a reply from a chip. The next field is the data payload that has a variable length depending on the type of transfer. Finally, an 8-b checksum (CRC) allows a check of the link integrity.

One bit is transmitted for each clock period. With a 40-MHz clock frequency, the fastest readout time is 150 μs for a counter size of 4 b. In order to use the detector in this fast readout mode, the countrate has to be lower than 106 kHz/channel to prevent counter overflow.

Except the address inputs, all connection to and from the BMC use Low Voltage Differential Signaling (LVDS) signaling to insure the lowest pickup noise.

The BMC uses a power supply voltage of 3.3 V and drains a current of 45 mA when the clock is present and all counters are counting noise ($\sim$ 60 kHz/channel when the offset is set to zero). Shutting down the clocks brings the current to 40 mA. Whether or not the counters are counting does not impact the power consumption by a significant amount.

C. Hybrid

The collector along with the six pairs of signal processing chips and some passive components are assembled on a ceramic hybrid. Conductive silver glue is used for the assembly. Connections to the chips are wire-bonded. This low outgassing assembly method makes the detector UHV-compatible.

The ceramic substrate has a diameter of 56 mm and a thickness of 0.7 mm. It is a standard double-sided hybrid with plated through holes vias.

D. Case

The case is made of aluminum with an outer diameter of 62 mm that allows the detector to fit most of the Scienta analyzers.

III. Detector Electronics

A block diagram of the complete high-speed detector system is presented on Fig. 5.

The detector is powered by a custom supply. In order for the detector to collect electrons, the front of the MCP stack needs to be set to the analyzer retard potential (up to 3 kV). Inside the detector, the charge collection works only if all voltages are referenced to the front of the MCP stack. To achieve that the whole power supply (high voltage for the MCP stack and low voltage for the signal processing chips) has to float at the analyzer retard potential. This component is critical to ensure the reliability of the detector. Particularly great care has been taken to ensure that all voltages collapse in the right order in case of an emergency shutdown.

The detector's serial link is connected to an optical interface to allow the use of optical fibers and to guarante a proper insulation between the detector floating at the retard potential and the DAQ system referenced to ground.

The digital input output (DIO) board located inside the data analysis computer is a commercial board (PCI-DIO-32HS from National Instruments). It has been chosen to avoid the development of a custom computer interface board. The DAQ board

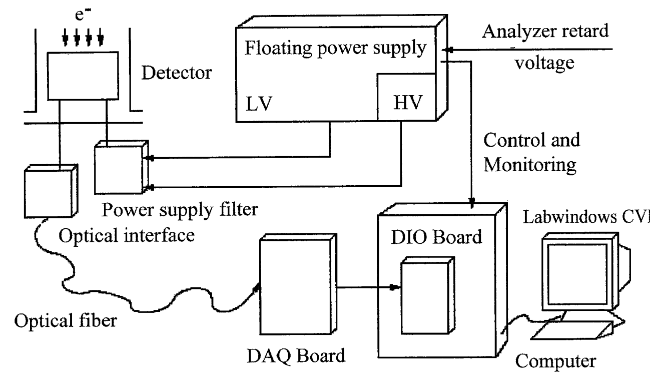

Fig. 5. System view of the high-speed detector.

interfaces the optical fiber serial link to the DIO board. It contains a field programmable gate array [(FPGA), XCV200 from Xilinx] that handles the communication with the DIO board and implements the serial protocol of the BMC. Seen from the DIO board, the FPGA behaves like a memory. Writing to some locations initiates the transmission of a command to the detector. The reply automatically fills other locations that can later be read by the DIO board.

The control software is written in the Labwindows CVI environment. A set of low-level functions provides the same interface as the original CCD-based detector. This allows an easy integration in the custom analyzer control software and enables crosschecks between the two detectors.

IV. Design Issues

A major design issue for the detector assembly is the simultaneous need for good thermal contact and electrical insulation.

The total power dissipation of the detector is 2.5 W and since it sits in the vacuum, a good thermal contact is needed between the heat source and the cooling system. On the other hand, high-voltage is present inside the detector and some elements need to be insulated from the others. The detector housing is at the analyzer retard potential and needs to be insulated from the grounded mechanical support. The ceramic of the hybrid has connection on both sides. It needs to be insulated from the detector base. This later is at the potential of the back of the MCP stack and has to be insulated from the case.

Thus, there are three interfaces that require a good electrical insulation (standing up to 3 kV) and a good thermal conductivity. The hybrid is glued to the base using vacuum compatible epoxy glue that combines good thermal conductivity and good electrical insulation. The base-case and the case-mechanical support interfaces use a sandwich of tin foil-Kapton-tin foil (Fig. 6). The Kapton is a good electrical insulator with a low thermal resistance while the tin foils are soft and can fill in irregularities in the surfaces for good thermal contact. The assembly can be separated at these two interfaces for disassembly and servicing.

The base plate is water-cooled and a chiller is not required to operate the detector. A sensor installed on the base is used to monitor the temperature and warn the user in case of overheating.

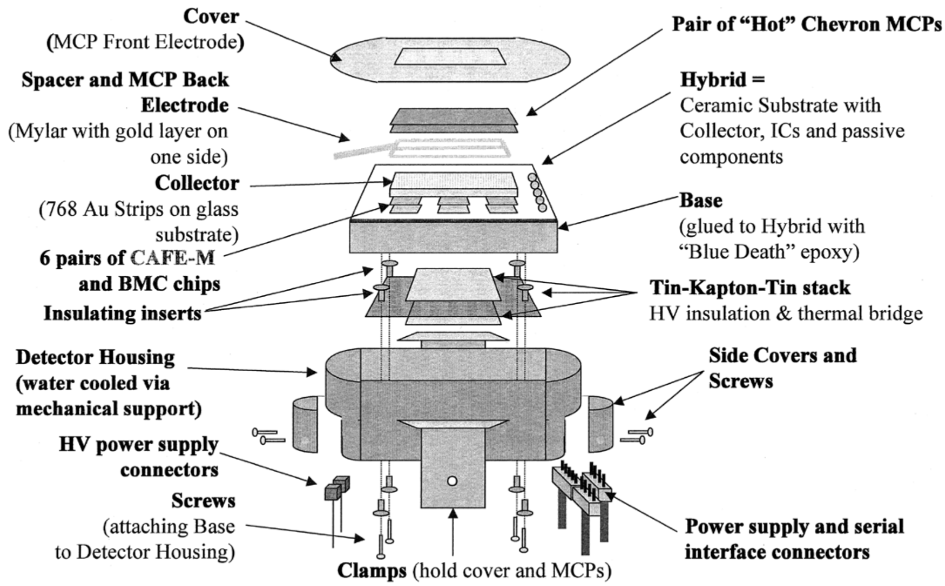

Fig. 6. Exploded view of the detector showing the main elements that insure good thermal conductivity and electrical insulation. There is another tin-Kapton-tin stack between the detector housing and the mechanical support that is not show here.

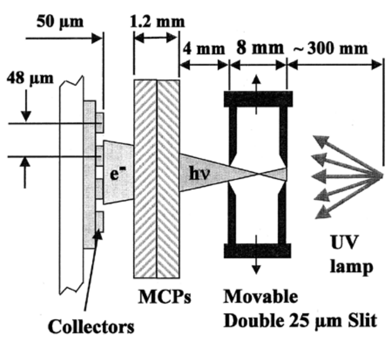

Fig. 7. Experimental setup for the measurement of the spatial resolution.

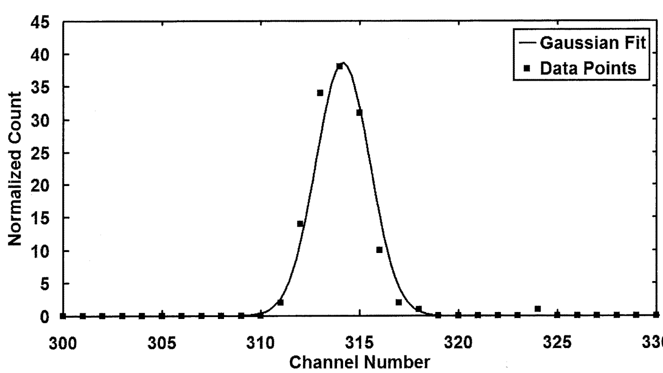

Fig. 8. Spatial resolution of the high-speed detector measured with a UV lamp and a 25 μm slit (cf. Fig. 7). Detector parameters were: MCP voltage $= 1.8$ kV, threshold $= 133$, integration time $= 50$ ms, average 50 spectra.

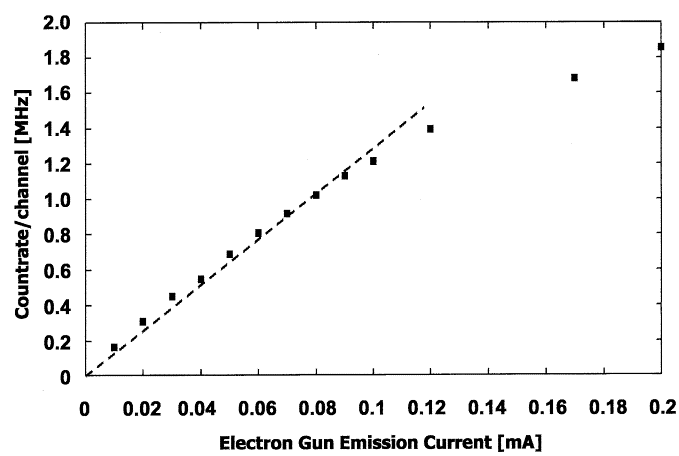

Fig. 9. Measured counting linearity of the high-speed detector using 25-eV electrons and a MCP voltage of 1.94 kV. Threshold was 39 and the integration time was set to 50 ms. Boxes are the data points while the dashed line represents the best linear fit.

V. Results

The detector has been tested first in a small test chamber. A UV lamp and a movable slit (Fig. 7) have been used to measure the spatial resolution (Fig. 8). The resolution (FWMH) is of 3.2 channels or 150 μm. In the test setup, the slit projects an image that is 50 μm wide on the detector. The measured resolution is in reasonable agreement with the test system capabilities since the pitch of the collector strips is 48 μm and there is some spreading of the charge cloud exiting the MCPs.

The spatial resolution is not affected by the MCP voltage once the plates are working in saturation. The threshold voltage does not change the spatial resolution as long as it is set such that the noise of the electronics is zeroed when no signal is present. A slight but no significant effect can be seen by changing the voltage between the back of the MCPs and the collector strips.

For The electron analyzer with a typical energy resolution of 2.6 meV/channel this spatial resolution translates in to an energy resolution of about 8.3 meV.

A preliminary linearity measurement (Fig. 9) has been performed with an electron gun. Since the double-pulse resolution of the CAFE-M is 50 ns, one can expect a linear counting region up to 2 MHz/channel. The first data show some nonlinearity and an inflexion point at around 1.4 MHz/channel. There are several possible explanations.

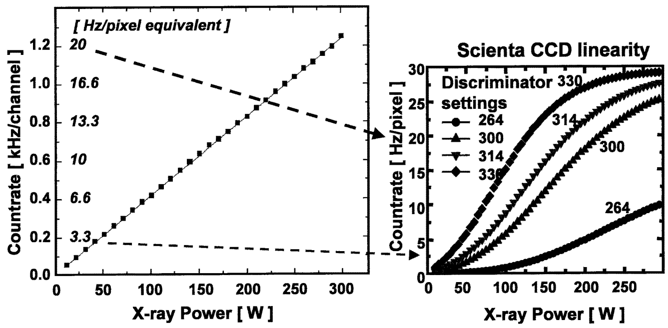

Fig. 10. Measured low countrate region of the high-speed detector and comparison with the existing CCD-based detector. This curve has been obtained with the detector installed in the electron analyzer and an aluminum K-α X-ray source. The sample used was MnO and the analyzer was set to look at the Mn 2P peak. The detector parameters were: MCP voltage $= 1.8$ kV and threshold $= 85$.

1) The calibration curve of the electron gun (number of electrons produced for a given emission current) has not yet been checked.
2) The MCPs actually used could saturate and show a nonlinear response when the signal current approaches 10% of the wall current ($\sim$ 100μA at 2000 V). Although a preliminary pulse-height distribution indicated that the MCPs were not driven into saturation, this has not yet been thoroughly checked.
3) The CAFE-M has originally been designed for the readout of silicon strip detector and thus for a small input charge range. With the large gain of MCPs, the amplifier can easily be driven into saturation. When saturated, the double-pulse resolution is degraded. Note: This can be corrected by designing a front-end electronics adapted to the MCPs but the CAFE-M has been used because it is a ready-to-use chip with performances close to the requirements of the high-speed detector.

Although the detector may possibly exhibit some nonlinearities that are under investigation, a zoom in the low countrate region (Fig. 10) shows that the detector clearly outperforms the actual CCD-based detector. The linearity curves from the CCD detector are from [8]. The Y-axis has to be scaled since the CCD is a two-dimensional (2-D) detector and countrate is expressed in counts per pixel. [8] also describes a calibration procedure that can easily be implemented if the detector were to be used in high-countrate experiments in its actual configuration.

[9] presents experimental results that were obtained with the detector installed in the electron spectrometer of beamline 4 at the ALS.

VI. Conclusion and Future Improvements

The linearity has to be checked and understood in order to meet the theoretical countrate goal of 2 MHz/channel.

Currently the DAQ timing is managed in software and thus there are some limitations due to the operating system. The best achievable timing is 5 ms of integration time and a repetition rate of one spectrum every 10 ms with a state-of-the-art computer.

Implementing the timing in hardware (in the DAQ board) will make it possible to reach the minimum readout time of 150 μs. The serial link of the BMC can operate up to a frequency of 60 MHz. It is thus possible to further reduce the minimum integration time. A further significant improvement would come from the use of a "parallel" readout. Instead of using a daisy chain to connect all BMCs, each of them would be read separately. This would add 10 more vacuum feedthroughs (bringing the total to 19—still a reasonable number). In this case and with a readout frequency of 40 MHz, the whole detector could be read in 56 μs with a counter depth of 16-b [10]. In addition to the improvement in the data quality, this solution would make the detector more reliable in case of the failure of one of the BMCs: only 128 channels would be lost while in the current implementation the whole detector is becoming unusable.

Another current bottleneck is the maximum speed at which the computer can read the detector. This limitation can be overcome by adding memory storage on the DAQ board. This solution is currently being implemented.

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