The MARS Photon Processing Cameras for Spectral CT

A thesis submitted in partial fulfilment of the requirements for the

Degree

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To my mother, and in memory of my father

Abstract

This thesis is about the development of the MARS camera: a standalone portable digital x-ray camera with spectral sensitivity. It is built for use in the MARS Spectral system from the Medipix2 and Medipix3 imaging chips. Photon counting detectors and Spectral CT are introduced, and Medipix is identified as a powerful new imaging device. The goals and strategy for the MARS camera are discussed. The Medipix chip physical, electronic and functional aspects, and experience gained, are described. The camera hardware, firmware and supporting PC software are presented. Reports of experimental work on the process of equalisation from noise, and of tests of charge summing mode, conclude the main body of the thesis.

The camera has been actively used since late 2009 in pre-clinical research. A list of publications that derive from the use of the camera and the MARS Spectral scanner demonstrates the practical benefits already obtained from this work. Two of the publications are first-author, eight are co-authored, and a further four acknowledge use of the MARS camera as part of the MARS scanner.

The work has been presented at three MARS group meetings, two departmental conferences, and at an internal Medipix3 collaboration meeting hosted by ESRF in Grenoble.

Contents

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Dave van Leeuwen, Marcus Clyne and Jethro Donaldson laid the foundations of the hardware and software systems that have gone into making a working camera. Dave and Marcus have supported me many times in practical as well as intangible ways: thanks, guys!

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Finally, I thank my brother-in-law Nigel Anderson for the spark that got me started on the MARS Project, and my sister Veronica for making sure that the fire didn't go out!

Glossary

ADC Analog to digital convertor. Electronic circuit that translates a physical voltage or current to an integer value. Used to allow a computer to access physical signals and perform algorithms using the digitised values.

Altera A major American designer and manufacturer of FPGA (q.v.) chips. Its best known competitor is Xilinx.

API Application program interface. The set of function calls (and associated code values or code names) through which a program can access a library of system functions. Operating systems provide many of their functions to user applications via a set of application program interfaces.

ASIC Application specific integrated circuit. Unlike most ICs (q.v.) which are mass produced for broad application, an application specific integrated is narrowly focussed on a single purpose, and may be funded by a single customer. Typically much more expensive than "off the shelf" ICs. The Medipix ASIC is a large array of identical pulse height analysers that is connected electrically to an array of pixelated sensors.

bash The standard command line interface or "shell" on Unix operating systems such as Linux and Mac OSX.

bias A voltage or current that sets a steady operating condition for a circuit such as a transistor amplifier, or for a diode. The value of the bias is selected to provide optimum performance of the circuit.

CAS A DAC (q.v.) on the Medipix chip. The Medipix3 v3.0 requires special handling of this DAC.

CERN The European center for high energy physics research in Geneva, Switzerland.

chip Common term for integrated circuit or IC (q.v.)

CISC Complex instruction set computer. A typical example is the Intel family of 80x86 processors, though they now contain an internal RISC (q.v.) machine.

CPU Central processor unit. Fundamental "engine" of a computer.

CSA Charge sensitive amplifier. A sensitive amplifier that can detect the presence of electrons in very small quantities, of the order of a few hundreds or thousands. Used in Medipix to amplify the tiny pulses from ionisation caused by x-ray photons.

CSM Charge summing mode: a feature of Medipix3 used to correct for charge sharing between pixels.

CT Computed Tomography. The use of computers to implement mathematical algorithms to "invert" x-ray projections and recover the two-dimensional structure of an object. Two dimensional slices can be combined to make three dimensional representations that can be visualised in pseudo-3D.

DAC Digital to analog convertor. Electronic circuit that translates an integer value to a physical voltage or current. Used by a computer to control external non-digital circuits, such as to set the offset voltage to an amplifier.

DDR RAM Dual data rate random access memory. Memory accesses occur on both transition of the clock line, doubling the potential data rate of memory read and write.

DECT Dual Energy Computed Tomography. A technique for extracting x-ray attenuation information from transmitted x-ray beams by varying the beam voltage, by running two separate x-ray tubes, or by stacking two detector systems on top of each other. Based on theoretical work of Alvarez and Macovski (1976).

DMA Direct memory access. A method in which data on a computer interface is transferred to and from memory without CPU (q.v.) involvement. Used when the fastest possible rates of data transfer are required, or when the CPU has other essential actions to be performed in the "foreground".

ESRF The European Synchroton Research Facility, in Grenoble, France.

FSR The Medipix2 fast shift register. Used to configure Medipix2 features, similar to Medipix3 OMR (q.v.).

GNU Gnu is Not Unix. A recursively named project to eliminate non-free software. Famous for programs like emacs and gcc.

GUI Graphical user interface. Common user-computer boundary, usually with mouse, windows and icons.

ILR A Christchurch electronics hardware and software design company, established by Marcus Clyne.

IP Internet protocol. The basic protocol used to carry data on the Internet.

EPROM Erasable programmable read-only memory. Digital data storage IC (q.v.) commonly used to store the program for a computer. Also used to store the configurating bits for an FPGA (q.v.). A Flash EPROM, which is now the norm, is erasable electrically, compared to the formerly common ultra-violet eraseable device.

FPGA Field programmable gate array. A chip with a collection of digital electronic circuits that can be connected to each other by loading a pattern of binary codes. Used to make specialised circuits. Can also be used to implement a microprocessor, such as the Nios2 32-bit processor used with Altera's chips.

Hex, Hexa Shorthand name of a MARS chip carrier with six Medipix chips fitted. A common alternative is the Quad (q.v.).

IC Integrated circuit. Electronic circuit fabricated using lithographic and chemical techniques on a single small crystal of semiconductor material. A microscopic version of a printed circuit board. Often referred to as a "chip".

I^{2}C Inter-IC interface. A two-wire digital signalling standard used to connect microcomputers to peripheral ICs. Similar to SPI (q.v.).

IEAP Institute for Experimental and Applied Physics, at Charles University in Prague, the Czech Republic.

JTAG The Joint Test Action Group. A standard setting body who specify physical interfaces and protocols for testing and probing ICs (q.v.).

LEP The Large Electron Positron collider. Predecessor to the LHC (q.v.).

LFSR Linear feedback shift register. A chain of binary storage circuits whose output is connected to its input through a logic function in a way that causes seemingly random patterns of bits. Can be used as a counter as well as a storage device. Both the MXR and the latest Medipix3 "RX" use this circuit to count pulses. The seemingly random series of patterns is sometimes described as a PRBS (q.v.).

LHC The Large Hadron Collider, a high energy physics experiment at CERN (q.v) in Geneva

LTC A firm that manufactures power supply connectors.

LVDS Low voltage differential signalling. A two-wire digital communication standard in which the presence of a 0 or 1 is indicated by two slightly different voltage levels in a pair of wires, for example about 1.5 V. The system is relatively good at not radiating interference, and is also quite insensitive to interference. It is used for almost all the digital signals to and from Medipix chips.

MAC Media access controller. The part of an Ethernet interface that performs encoding and decoding of data to be transmitted and received by physical voltage levels and transitions.

MARS Medipix All Resolution System. The name of a project to implement Medipix chips in pre-clinical Computed Tomography.

mccli MARS Camera command line interface. A PC program that was developed the thesis work for testing and exploration of the Medipix chips in a MARS camera. Options are specified on the "command line", allowing easy automation of repetitive operations in a script.

MXR A variant of Medipix2, named after its principal designers: Michael, Xavi, and Rafa.

NIKHEF The Dutch national organisation for High Energy Physics research, based in Amsterdam.

OMR The Medipix3 operation mode register. Bit settings in this register configure most Medipix3 functions. Similar to the Medipix2 FSR (q.v.).

pcb Printed circuit board. Semi-rigid plane insulating board with conductive "tracks" connecting electronic devices. There may be several separate layers of tracks in parallel inside the board. These can be interconnected by conductive "vias". There may be a layer dedicated to providing a ground plane, and another, or several, with power supplies. ICs (q.v.) and other electronic components are connected to the tracks by solder, wire bonds, and other methods.

PEM Brand of threaded fasteners for mounting a pcb (q.v.).

PHYTER Trademark of a family of Ethernet interface chips from National Semiconductor.

PRBS Pseudo random binary sequence. A pattern of binary numbers produced by some kinds of feedback register circuits. Sometimes used as a form of simulated noise. For a known circuit, the position of a pattern in the sequence of possible patterns allows a count to be reconstructed.

Quad A MARS chip carrier with four Medipix chips fitted.

RISC Reduced instruction set computer. A computer architecture with a relatively limited set of machine instructions of fixed format. Programs tend to be bigger than for a CISC device (q.v.), but can run faster.

RS232 The name of a basic low speed digital communication system. Can carry data at rates up to 100,000 bits per second without a separate clock. Also known as "async", for asynchronous (unclocked) signalling.

SCSI The small computer system interface. A bus standard for high performance communication between computers and devices such as disk drives.

SPI Serial peripheral interface. A three wire digital interface for communication between a microcontroller and its peripheral chips. Similar in purpose to I^2C (q.v.). Example SPI devices on the MARS Caemera readout are an ADC and some DACs (q.v.).

TCP Transmission control protocol. A robust protocol for carrying data over an IP (q.v.) network. Able to detect loss of data, and to work around network failures.

USB The universal serial bus. High speed (10s to 100s of Mbits per second) general purpose signalling system used to interconnect computers and peripheral devices.

USB-JTAG interface Converter box or "dongle" providing access to JTAG (q.v.) via a USB cable.

Timepix A variant of Medipix2 with Wilkinson counter features.

UDP The universal datagram protocol. A protocol for carrying data over the Internet. Less sophisticated than TCP (q.v) because lost data is not retransmitted, but simpler to implement and slightly faster in throughput.

Chapter 1

Introduction

Contents

1.1 Goal

The goal is to develop a new generation of spectral x-ray CT scanners for pre-clinical and, eventually, human imaging, based on the Medipix3 detector developed at CERN. A project to this end has been running at the University of Canterbury, with support from the Universities of Auckland and Otago, and with financial assistance from government and industry. To approach this goal, a small, bench height spectral CT scanner, the MARS (Medipix All Resolution System) CT scanner (Figure 1.1), has been designed and built by the MARS team in Christchurch, New Zealand. The scanner had by 2009 already gone through several cycles of refinement.

The goal of my PhD project is to develop a camera based on Medipix detectors, a camera suitable as a testbed for several variants of Medipix chips, with various sensors, various array sizes, and with sufficient speed of performance to meet the time requirements of biological CT image making. Test cameras are to be used for characterisation of sensor behaviour, to gather data to exercise CT acquisition and reconstruction algorithms with analogues of biological tissues, and to create images for new science from biological materials and living tissue.

Figure 1.1: The MARS CT scanner

1.2 Motivation

In medicine, Computed Tomography (CT) is a workhorse of diagnostic radiology, as well as being a support tool in radiotherapy and in the operating theatre. Mainstream CT still relies on black and white imagery due to the inability of standard radiation sensors to discriminate the continuous range of energies of x-ray photons in a vacuum tube beam. Dual Energy CT is a hybrid solution, sophisticated, complex and expensive, that offers valuable discriminatory functions by duplicating elements of a standard CT scanner with some compromises.

The ideal way forward for CT is to find a radiation detector that can discriminate photons by energy. Medipix was conceived to satisfy this demand (although it has other applications too), and its spatial resolution was set to match that of mammography, a particularly demanding screening (pre-diagnostic) application of radiology. The MARS camera, using Medipix, offers polychromatic energy sensitivity. This will allow reduced dosage through more efficient use of contrast media. It will generate new information about normal and abnormal tissue composition through elemental analysis using energy-dependent x-ray absorption.

1.3 What is Medipix?

Medipix is to x-ray instruments, such as CT scanners, what a colour television camera is to a studio that broadcasts black and white TV. Unlike the detectors in mainstream CT scanners, Medipix is able to measure the energy spectrum of the x-ray photons that fall on each fine grained sensing element or "pixel".

Medipix is a hybrid chip, made of two fabricated semiconductor crystal slices. The sensor layer, divided into pixels in a square array with approximately 330 pixels per square mm, is connected by bump bonds to the signal processing analog and digital layer, an application specific integrated circuit (ASIC).

Medipix needs an electronic readout environment. Readouts have been developed and supplied commercially to users by institutions in the Netherlands and the Czech Republic. A readout supplies DC power and provides control and communication signals. Medipix also needs a high voltage bias supply, cooling, and a supporting surface and printed circuits to connect to via wire bonds. Some of these requirements are available from existing readouts; the MARS Camera provides them all in a compact, standalone and flexible package.

Medipix is a direct spin-off from the extensive scientific project that is operated by CERN. CERN, conceived in the early 1950s and located in Geneva, is a cooperative multi-nation venture to investigate fundamental particle physics using high energy accelerators, colliders and associated detector technologies. A series of breakthroughs in the energy and detection of particle collision and collision products has taken place since the 1950s at CERN. Such work there, and at other centers around the world, has stimulated invention in acceleration, superconducting magnets, cryogenics, vacuum creation, and particle and radiation detection. CERN is the world centre of high energy physics research due to its Large Hadron Collider, the largest and most powerful accelerator and collider in existence. Recording and interpreting its observations depended upon comparable improvements in computer processing power, and in software such as the World Wide Web. Hypertext transport protocol (HTTP) and hypertext markup language (HTML), the fundamental WWW communication protocol and display language, were conceived and developed by Tim Berners-Lee at CERN. His purpose was to facilitate communication among the extensive team of scientific and technical workers who developed the Large Electron Positron collider (LEP), predecessor to the LHC, and the idea has taken wing.

The precursor devices to Medipix were developed by a team that implements particle and radiation detectors for CERN, most recently for the LHC. CERN is a costly investment for the governments that own it, and the intellectual property behind Medipix is one of a number of valuable products that CERN offers to outsiders for the economic benefit of both parties. Medipix is now in its third generation, Medipix3, and is co-funded by CERN and external collaborators. The collaborators are nationally diverse government and university research institutions. The MARS Project, funded by the New Zealand government, New Zealand universities and business, is a member of the Medipix3 collaboration through the University of Canterbury.

1.4 The route to a camera

What is my thesis about? It is about the electronics, FPGA logic, microprocessor firmware and PC interface software for the MARS camera. I did much of the initial troubleshooting of the hardware from shortly after its prototype release, and gradually took over responsibility for finding and fixing problems in, and enhancing, the motherboard microprocessor firmware and PC interface software.

The electronics and FPGA logic was supplied by ILR, a Christchurch company. The initial microprocessor firmware for the motherboard, and the firmware for the high voltage board, was also supplied by ILR. The motherboard microprocessor firmware was extended by me to improve camera performance and to support new features such as Peltier cooling. During the development of the camera there have been several revisions to the motherboard, high voltage board, and Medipix chip carriers, and I was intimately involved in initial testing and fault finding of the various changes to this hardware.

The PC software started as a collection of Python test programs developed at the University of Canterbury. It worked through the standard UDP/IP protocol over a Gigabit Ethernet interface to carry the proprietary MARS camera protocol to and from the camera, which supports the same local area network physical hardware and software layers. I took over the Python code, while its initial developer worked to implement a system library program, `libmars-camera` in C source code. `libmars-camera` implemented the essential camera interface functions and exported them via a public application programming interface (API) for use by the MARS Spectral system software. I found and fixed some faults, and extended the Python code with various missing functions; my work was translated to C by the original developer and added to the library. After the library had reached stability I took over its maintenance and development.

At the time that I started working with the camera, a built-in diagnostic interface, working over an RS232 port, was used by the hardware developer for testing of new camera features, and there were some problems in the local area network protocol which had not been resolved. These problems lingered, in part, because the Python code could not be fully tested on the hardware developer's working PC. Consequently, some of my initial work required resolution of low level incompatibilities in the MARS protocol that carries commands and responses between the PC and camera.

1.5 Chronology

In 2008, the University of Canterbury joined the Medipix3 collaboration as a foundation member, with the University spinout company MARS Bioimaging Ltd obtaining exclusive rights to use Medipix in human CT and in small animal CT.

Towards the end of 2008 the decision was made to commission a new camera, because the existing readout options were not sufficiently compact or flexible. ILR received the contract to deliver the electronic hardware and firmware for the camera. University of Canterbury staff and students began developing PC device driver software.

I was a student newcomer in 2009, bringing experience in embedded system development. In April 2009 I was asked to take over the software development of the camera firmware. A preliminary version, not yet able to capture images, was working on a prototype based on an Altera FPGA development kit. The first image, of alpha particles from an americium source, was obtained from a Medipix2 MXR in mid May 2009. This working system was demonstrated at a meeting in France later that month.

The first Medipix3 sample to be handed to a collaboration member was brought back from Europe in June. The chip had no sensor layer, but was suitable for initial trials of the MARS readout. It gradually became evident from hands-on experience that the chip had several design faults. In December 2009 the CERN chip designers released updated documentation giving workarounds for some of the problems. These workarounds are currently in use, but are expected to become unnecessary when redesigned Medipix3 chips emerge from manufacture and hybrid assembly (bump bonding).

In 2010 the first complete readout electronic printed circuit board (pcb) was produced. Two versions of the chip carrier pcb were designed and produced; there are separate versions for Medipix2 and Medipix3. The Medipix3 chip carrier allows from one to six chips to be fitted in a 2x3 tiling. One Medipix2 based chip carrier, with two MXR chips bearing CdTe sensors, has been assembled.

In early 2010 the MARS readout was made to work with a Medipix3 by ILR, using assistance from CERN. I had reduced my involvement after learning that there were undocumented chip problems during Medipix3 trials in later 2009, but returned to software development in May 2010. In September the first multi-chip Medipix3, a 2x2 assembly called the Quad, produced images.

Using a pair of modified high voltage boards in a daisy chain, the dual CdTe MXR system was usable from May 2011.

Images with a fully populated Hex camera (six-chip), using CdTe as the sensor material, were taken in May 2011. There were some image quality problems, as well as a missing wire bond, which reduced the usability of this camera.

In 2011 the high voltage pcb was enhanced with improved stability and range at high voltages (up to 500 V). Peltier device power, sensing and control circuitry was added, as well as a fan and temperature monitoring device to allow controlled cooling of Medipix.

Since the beginning of 2010, data transfer from Medipix to PC has been made faster through stepwise improvements in the serial readout process. For multi-chip Medipix3 cameras, all chips are clocked simultaneously and network packets are sent in a homogeneous stream without the overhead of message-by-message handshaking to the PC.

1.6 Chapter outline

CHAPTER 2 introduces some of the basic physics of x-rays and their interactions with matter. Introduces computed tomography. Discusses energy-related photon behaviour and suggests a method for pixelated semiconductor sensors to measure the energy of single x-ray photons. Lists some of the applications of energy sensing in computed tomography.

CHAPTER 3 gives a short history of the innovative photon processing x-ray imaging chip, Medipix3. Explains the rationale for building a dedicated readout system, the MARS camera, around versions of Medipix, to make an energy resolving x-ray camera for the MARS spectral CT scanner.

CHAPTER 4 organises and lays out the physical, electronic and functional specifications of Medipix2 and Medipix3. Records some of the new knowledge gained about Medipix during development of the MARS Camera.

CHAPTER 5 describes the electronic hardware that provides power and bias voltage to, control over, and communication with up to six Medipix chips. Lists the logical subsystems implemented in “soft logic” in a field programmable gate array or FPGA. Gives a brief survey of the chip carriers for Medipix, including those designed for the MARS camera. Describes the mechanical components that provide a cooled enclosure for the Medipix chip carrier, motherboard, and high voltage board.

CHAPTER 6 summarises the functions implemented in the program or “firmware” that runs on the FPGA-resident Nios2 CPU inside the MARS camera. The program is constructed from an “executive loop” that waits for and performs commands under remote control via the Gigabit Ethernet LAN, using the IP/UDP networking protocol. The firmware uses low level functions interfaced to FPGA logic blocks. Using serial and parallel digital protocols, Medipix chips are controlled, programmed and their counters are read out. Other electronic subsystems in the camera are similarly managed. In the external direction, the firmware calls vendor-supplied device and network functions. These give access to a proprietary FPGA implementation of Gigabit Ethernet, through which the scanner PC controls the camera.

CHAPTER 7 identifies and documents the public application programming interface `libmars-camera`. The API runs on the scanner PC and gives user applications a pathway to configure, control and take images with the MARS camera. Describes the features and user interface of a command-line based test utility, `mccli`, that provides standalone control of the MARS camera using API calls.

CHAPTER 8 outlines the Medipix3 pixel equalisation mechanism. Shows the results of measurements of the behaviour of noise sources used to perform equalisation.

CHAPTER 9 describes two tests of the Medipix3 charge summing mechanism, and discusses the results from performing these tests: one with alpha particles, the other with gamma photons, emitted by ^{241}Am.

CHAPTER 10 states the contributions that I made in the work that led to this thesis. The significant stages in development of the camera are listed. The state of development of Medipix3, and proposed ongoing research with the chip in Spectral CT, is discussed.

1.7 Outcomes of my research

The MARS Camera was first used for research work in the latter part of 2009. Since then, a growing number of workers in New Zealand and overseas have used the camera, both inside and outside the MARS CT scanner. Publications resulting from work which depended on the use of the camera are presented here, broken into three groups. In the first two papers, I was first author. In the second group of eight papers, I was co-author. In the third group, the MARS scanner, which uses the MARS camera as its imaging device, was acknowledged and consequently the research work was derived directly from my work.

1.7.1 Papers for which I was first author

- R M N Doesburg, T Koenig, S J Nik, S T Bell, J P Ronaldson, M F Walsh, A P H Butler, and P H Butler. Spectrum measurement using Medipix3 in charge summing mode. *Journal of Instrumentation*, 7(11), 2012

New results with Medipix3 in charge summing mode and a CdTe sensor layer are reported for the gamma photon spectrum of ^{241}Am. Although the chip was not equalised, clear spectral features are visible, compared to almost total absence of peaks seen with Medipix2 CdTe detectors that do not have charge summing mode. I shared the data gathering work and performed all of the statistical analysis.

- Robert Doesburg, Marcus Clyne, David van Leeuwen, Nick Cook, Anthony Butler, and Philip Butler. Fast ethernet readout for Medipix arrays with MARS-CT. In *IEEE Nuclear Science Symposium and Medical Imaging Conference*, Oct 2009

  This poster, with a specification and diagrams of the MARS camera, was presented on our behalf by Stuart Lansley at the 2009 IEEE Nuclear Sciences Symposium. Because none of the authors were present at the conference, there is not a record in the conference proceedings. I prepared the poster.

1.7.2 Papers for which I was a co-author

- R Zainon, JP Ronaldson, T Janmale, NJ Scott, TM Buckenham, APH Butler, PH Butler, RM Doesburg, SP Gieseg, JA Roake, and NG Anderson. Spectral CT of carotid atherosclerotic plaque: comparison with histology. *European Radiology*, Jul 2012. doi: 10.1007/s00330-012-2538-7

  Algebraic and statistical material discrimination methods are applied to CT images of surgically removed human atherosclerotic plaque. The images are made with a silicon Medipix3 version of the MARS camera in the MARS CT scanner. Lipid, calcium/iron and water can be distinguished, and the calculated material quantities correlate well with histological stains applied to the same samples.

- Qiong Xu, Hengyong Yu, J. Bennett, Peng He, R. Zainon, R. Doesburg, A. Opie, M. Walsh, Haiou Shen, A. Butler, P. Butler, Xuanqin Mou, and Ge Wang. Image reconstruction for hybrid true-color micro-CT. *IEEE Transactions on Biomedical Engineering*, 59:1711–1719, Jun 2012

  Virginia Tech researchers visited our lab in September 2011 and helped to make the first CT scan of a live mouse in the MARS scanner, using the MARS camera with quad Medipix3 chips, after I had developed a significant firmware speed up. Our observations were used in support of a project at Virginia Tech which is developing advanced techniques based on algebraic reconstruction algorithms and interior reconstruction methods. The paper presents results from the live mouse scan, and describes concepts for a scanner that will use the Medipix3 spectral sensor in synergistic combination with non-spectral sensors in a radical CT scanner design.

- M.F. Walsh, R.M. Doesburg, J.L. Mohr, R. Ballabriga, A.P.H. Butler, and P.H. Butler. Improving and characterising the threshold equalisation process for multi-chip Medipix3 cameras in single pixel mode. In *IEEE Nuclear Science Symposium and Medical Imaging Conference*, pages 1718–1721, Oct 2011a

  New equalisation algorithms for the MARS camera with quad silicon Medipix3 detectors have been developed in the MARS team. In this test, three out of four chips give good results, while the fourth has some pixels that can not be shifted close to the baseline. X-ray images taken of a USB drive after equalisation are significantly improved compared to the unequalised version. My work on equalisation contributed to the development of the algorithm used.

- A Butler, P Ronaldson, M Walsh, R Aamir, R Doesburg, N de Ruiter, N Scott, R Zainon, S Gieseg, T Woodfield, A Siegert, J Mohr, N Anderson, and P Butler. Development of a Medipix3 based spectral (multi-energy) CT for pre-clinical evaluation of biomarkers. In *Royal Australian and New Zealand College of Radiologists Annual Scientific Meeting*, Oct 2011

  In this conference talk a survey is given of new results in spectral CT. The MARS camera was used for many of the images displayed in this wide-ranging talk.

- R Aamir, S P Lansley, N G Anderson, P H Butler, A P H Butler, R M Doesburg, J L Mohr, M F Walsh, S J Nik, and R Zainon. Characterization of Si, CdTe and GaAs sensor layers on Medipix assemblies using micro-focus x-ray sources. In *IEEE Nuclear Science Symposium and Medical Imaging Conference*, Oct 2011a

  This conference paper reports on extensive work that was done with the dual CdTe MXR MARS camera to enhance the image quality and overcome a variety of flaws in the CdTe sensor layers on the two chips. Flat fielding leads to significant improvement in images. Observations were made of the observed versus expected noise in CdTe, and a saturation effect is seen as the photon flux is increased. A CT image of a mouse is presented. Work is also reported from characterisation of a silicon Medipix3 in the MARS camera.

- R Aamir, M F Walsh, S P Lansley, R M Doesburg, R Zainon, J J A de Ruiter, P H Butler, and A P H Butler. Characterization of CdTe x-ray sensor layer on Medipix detector chips. In *Conference on Advanced Materials and Nanotechnology 5*, Feb 2011b

This poster summarises a comprehensive series of observations and measurements taken on a dual CdTe MXR MARS camera with a specially constructed high voltage power supply. This camera has been the mainstay of CdTe imaging in the MARS team. CdTe is a complex material to use as a sensor layer and has a number of distinctive characteristics, not all of them fully understood.

- M.F. Walsh, A.M.T. Opie, J.P. Ronaldson, R.M.N. Doesburg, S.J. Nik, J.L. Mohr, R. Ballabriga, A.P.H. Butler, and P.H. Butler. First CT using Medipix3 and the MARS-CT-3 spectral scanner. *Journal of Instrumentation*, 6, Jan 2011b

  This paper presents the first CT image taken with a Medipix3 chip. Syringes with various markers are used as test objects. The MARS camera was used to take the x-ray projections in the MARS CT scanner. Medipix3 charge summing mode is evaluated using alpha particles in a standalone camera. In this mode, multi-pixel hits are successfully shown to be reduced to single occurrences.

- J P Ronaldson, M Walsh, S J Nik, J Donaldson, R M N Doesburg, D van Leeuwen, R Ballabriga, M N Clyne, A P H Butler, and P H Butler. Characterization of Medipix3 with the MARS readout and software. *Journal of Instrumentation*, 6, Jan 2011a A comprehensive overview is given of Medipix3 performance in the MARS camera, both as a standalone x-ray device and as an imager in the MARS CT scanner. Pixel equalisation is performed in single pixel and charge summing mode and the results compared. Charge summing mode gives poor results, in line with reports from the manufacturer. Single pixel mode performs well, and it is possible to distinguish materials of non-biological as well as biological tissue. Some issues with temperature stability in some DACs are noted. Overall, Medipix3 is shown to be suitable for use in ongoing research.

1.7.3 Papers that acknowledge the MARS scanner

Four additional papers acknowledge use of the MARS CT scanner, which includes the MARS camera, or the camera alone. Therefore, my work to develop the camera was a direct contribution to the science reported here:

- John Paul Ronaldson, Rafidah Zainon, Anas Sedayo, Nicola Scott, Anthony Butler, Phil Butler, and Nigel Anderson. Towards quantifying the composition of soft-tissues by spectral CT imaging with Medipix3. In *Radiological Society of North America: 97th Scientific Assembly and Annual Meeting*, Nov 2011c

  At this very large assembly of radiologists, results are given of a study to determine if spectral CT can quantify fat, calcium and iron in soft tissues. A Medipix3 detector in the MARS camera, and microfocus x-ray tube in the MARS CT scanner, were used. As well as phantoms, the quantification method was validated in biological specimens.

- J. P. Ronaldson, R. Zainon, N. G. Anderson, A. P. Butler, and P. H. Butler. The performance of MARS-CT using Medipix3 for spectral imaging of soft tissue. In *IEEE Nuclear Science Symposium and Medical Imaging Conference*, Oct 2011b

  Results are reported from systematic tests of a single silicon Medipix3 detector in the MARS camera. The camera is used to take projections in the MARS CT scanner. Measures of image quality including modulation transfer function and image noise are made. Phantoms containing analogues of soft tissue, including fat and calcium, are imaged and the linearity of Hounsfield Unit measurement is assessed. CT images are made of human arterial plaque, and of mouse kidneys enhanced with contrast medium. The results demonstrate that the Medipix3 MARS camera, running in single pixel mode, is acceptable for research applications.

- Shuai Leng, Lifeng Yu, Jia Wang, Joel G. Fletcher, Charles A. Mistretta, and Cynthia H. McCollough. Noise reduction in spectral CT: Reducing dose and breaking the trade-off between image noise and energy bin selection. *Medical Physics*, 38, Sep 2011

  A team including Mayo Clinic staff is testing a new algorithm to reduce noise by taking advantage of photon counting chips in spectral CT. A Medipix2 sensor in a MARS camera is used, with phantom data, for comparison with a Dual Energy CT system, and shows promising results.

- Steven M. Jorgensen, Diane R. Eaker, and Erik L. Ritman. Biomedical spectral x-ray imaging; promises and challenges. In *Proceedings of SPIE: Medical Applications of Radiation Detectors*, volume 8143, Aug 2011

  Mayo Clinic CT researchers have been using the MARS camera with the Medipix2 MXR since 2009, and a camera with Medipix3 since it became available in 2010. They discuss the potential of spectral CT using the new techology, and give a number of results obtained with Medipix3 in charge summing mode.

Chapter 2

Spectral CT

Contents

2.1 X-ray tube energy spectrum

The x-ray photons used in medical CT are relatively easy to produce, requiring only a vacuum tube with a heated cathode and an anode at high potential: 50,000 to 120,000 volts. The original version of the device was not invented by Roentgen in 1895, but it was he who noticed that it produced penetrating radiation that lit up a piece of paper coated with scintillating material. The tube cast shadows of the interior structure of interesting things, such as that of his own and his wife's hands, on this accidental radiation imaging detector.

It was later found that the x-ray energy spectrum includes a continuous, broad, and smooth band of energies. This is caused by bremsstrahlung, German for "braking radiation", since the sudden deceleration of high velocity electrons is the cause of x-rays. In addition to the smooth energy band, if the graph of photon flux versus energy is plotted it shows narrow spikes of energy. These spikes are caused by fluorescence from the metallic elements in the target anode. The energy at which the spikes appear is related in a simple way to the atomic number of the element in the anode. Finally, there are sudden decreases in flux with increasing energy at some points, caused by photoelectric absorption in the target and window materials.

The detailed theoretical explanation of bremsstrahlung x-ray emission was given by Bethe and Heitler more than thirty years after Roentgen's discovery, based on the mature quantum theory.

Earlier, Henry Moseley demonstrated in experimental work in 1913 the relationship between atomic number and the energy (wavelength) of fluorescent x-rays from excited metals. His work was powerful evidence for the new theory of the electronic structure of atoms, of Rutherford, Bohr and others. The material-specific fluorescence is called "characteristic radiation".

2.2 X-rays pass through matter

X-rays pass through matter, but not all of them. X-rays of lesser energy, called soft x-rays, are fairly strongly attenuated by matter. The denser the matter, and the higher the atomic number, the more the attenuation. For higher energy, hard x-rays, attenuation is initially less but still falls off with higher density and atomic number.

In this context, attenuation refers to the change in intensity of a beam of x-rays. If the measured intensity of the beam is reduced due to the presence of matter between the source and the point at which the measurement is made, the beam is said to be attenuated. A beam can be attenuated by the scattering of photons in direction away from its initial path. A beam can also be attenuated by the annihilation of photons; in this case absorption is taking place. From the point of view of the measurement, there is no distinction between scattering and absorption; there is only a decrease, or attenuation, of intensity.

Superimposed on the gradual reduction of attenuation with increasing photon energy, and the increase of attenuation with density/atomic number, a complementary effect of Moseley's law is seen. In this process, instead of photons being created by fluorescence, they are absorbed, in the same location as that from which characteristic radiation is created. When x-ray photon energy is slightly higher than the binding energy of inner-shell electrons, there is a sharp increase in x-ray attenuation, caused by energisation of an electron and annihilation of the photon (the Photoelectric Effect). For the innermost orbital, the K-shell, this discernible sharp jump in attenuation is referred to as a K-edge. There are edges for orbitals further from the atomic nucleus: L-edge, M-edge, and so on. As Moseley observed, these binding energies are unique to atomic number, and the energy at which an edge occurs allows an element to be identified.

Apart from the photoelectric effect, photons interact with atoms in Rayleigh or "coherent" scattering, in which photons change direction but do not lose energy due to simultaneous interactions with many atoms at once. Also possible is Compton or incoherent scattering, when the photon loses energy after interacting with loosely bound electrons. This is caused by the Compton effect, after the theoretical explanation and experimental demonstration of this relativistic mechanism was found and published by Arthur Compton in 1923. The combined effect of all these interactions is to remove photons from an x-ray beam. Photons may be completely absorbed, or may be scattered in a new direction. Photons that were not travelling toward the detector may be scattered in its direction, causing a loss of contrast.

The energised electrons caused by the photoelectric and Compton effects eventually lose most of their energy in repeated collisions with other electrons which are themselves energised. The final result is a large number of electrons that have been separated from the bound state, and matter that is ionised.

The combination of Rayleigh scattering, Compton scattering, and the photoelectric effect causes the transmitted x-ray beam to carry, or to be imprinted with, information that characterises the material through which the beam has passed. The encoded information is used quantitatively in applications such as bone densitrometry and in airport security scanning of luggage and cargo.

2.3 Detecting x-rays

X-rays are detected by placing matter in their path and measuring the degree of ionisation that they cause. Ionisation can be detected by its downstream effects: scintillation in crystals and organic substances; the catalysis of silver halide crystals in photographic film, causing it to darken; discharges in an electric field in gas; the formation of clouds in supersaturated gas; the formation of bubbles in liquids; the buildup of clouds of electrons and holes in a solid; and the generation of electrical pulses on the faces of semiconductor crystals that have an imposed electric field.

This last effect, the generation of pulses in semiconductors, is the phenomenon used in the photon counting x-ray detector, which is a new technology under active research and development. The first CT scanner (or EMI scanner as it was known) worked in a different way. The EMI scanner used a sodium iodide crystal as a scintillator, and a photomultiplier tube. For a while, into the mid 1990s, xenon discharge tubes were the preferred detector. Discharge tubes are limited in efficiency, and ceramic scintillators with photodiodes are now standard in commercial CT scanners.

CT systems based on scintillators and photodiodes indirectly measure x-ray intensity. Photons of visible light from the scintillator create clouds of charge carriers by ionisation in the photodiodes. The photodiodes produce a current, proportional to the number of light photons, but conceal information about the individual photon energies.

In a pulse based detector, the size of the pulse of ionisation caused by a single photon is proportional to its energy. A pulse height analysing system can count photons and measure their energy. A detector that is spatially extended with pixels that have individual pulse height analysers, and used to measure an x-ray beam on a photon by photon basis, can produce a map of beam structure from which material information can be decoded. Medipix is one of the first such detectors, and is amongst the devices with the highest spatial resolution.

2.4 Computed tomography

Computed Tomography, or CT, is an extension of x-ray image making, from shadowgrams to synthetic calculated cross sections. The original projections of a three dimensional object to the two dimensions of a film or fluoroscope presented invaluable information to medical practitioners, as well as to many other workers who could make decisions based on "seeing inside" what was normally invisible. A foreign body like a bullet, a broken bone, dangerous masses in the brain, or the deposits of bacterial infections like tuberculosis in the lungs; the fit of a person's foot in a shoe; the presence of cracks in welds: these are just a sample of the many forms of illumination that are gained from the use of x-rays using methods similar to that originally discovered by Roentgen, in 1895.

The mathematical problem of calculating the internal structure of an "opaque" object, by combining the information from a series of two dimensional projections or shadow-grams taken from different angles, was solved in the early twentieth century (Radon, 1917). A relatively straightforward mechanical technique, based on rotating or translating an x-ray source and its detector about an object and relying on blurring of regions away from the centre (or axis) of movement, was developed early on (tomograms). Work was done on the "reconstruction problem" in radio-astronomy in the 1950s, and in electron microscopy in the 1960s. Pioneering work was done in Russia and South Africa. But it was the availability of compact and affordable small computers, along with an inventor's curiosity, which led Godfrey Hounsfield - and his employer EMI - to develop and commercialise a revolutionary new medical instrument around 1972: the EMI Scanner or CAT Scanner (Computerised Axial Tomography). Hounsfield, along with Alan Cormack, received the Nobel Prize in Medicine (1979) for the development of this new technology.

CT is now ubiquitous within diagnostic radiology and in other areas inside and outside clinical medicine. It uses the x-ray detection methods that have been in use for more than a century: initially scintillators with photomultipliers, and gas discharge tubes, and more recently scintillating materials with indirect solid state optical sensors.

2.5 Spectral CT

Research published by researchers from several groups within Philips (Schlomka et al., 2008) won a best-paper award from their journal. Their topic, about which they used the term “Spectral CT”, was named to distinguish their work from the Siemens product DECT, Dual Energy CT. The Philips group are exploring one of the new kinds of energy resolving x-ray detectors. I am going to explain what I mean by Spectral CT and describe the technology that makes Spectral CT an exciting new tool for preclinical radiology, and a contender in Medical Imaging.

By Spectral CT, we mean the use of x-ray photon energies to enhance the information content of CT images. The photons from an x-ray tube have a spectrum of energies caused by several processes: bremsstrahlung, fluorescence and K-edge absorption. It is difficult (outside a high-energy physics laboratory) to produce an x-ray beam that does not have a broad and complex energy spectrum. At the same time it has always been, and for mainstream manufacturers still is, difficult to distinguish the energy of x-ray photons at the detector. The spectral content of the beam from an x-ray tube creates difficulties due to the way the photons with diverse energies interact in living tissue (beam hardening is an example). The unavoidable reality of the x-ray spectrum has potential benefits. DECT, which leads the way commercially, is beginning to enable powerful new diagnostic methods. However DECT is a mechanically complicated system, and the new technology of solid state photon counters, and perhaps most importantly the imminent arrival of working photon processing counters, may lead the way to a simpler detector design with much more to offer in new diagnostic tools.

2.6 Processing photon events

A semiconductor crystal can be formed into an array of small independent segments, usually called pixels (from “picture elements”). Each pixel can be connected to its own pulse height analyser. When a photon ionises material local to the pixel, a pulse occurs and it can be measured and counted. The number of counts is a measure of the intensity of x-ray photons at one localised area, usually square or rectangular, in space. Pixels in visible light detectors can be manufactured with dimensions of a few μm, providing spatial resolution that rivals film. The combination of high spatial resolution with energy resolving capability is the great promise of photon counting x-ray detectors (hybrid pixel detectors such as Medipix have pixels a few tens of μm square due to manufacturing constraints).

Pixelated photon counting x-ray detectors are limited by an awkward trade-off. The size of the cloud of ionised charge from an x-ray photon is comparable to the desirable fine-grained pixel size. Like Buffon’s Needle experiment (in which a needle is dropped onto a surface with criss-crossing horizontal and vertical lines, and the number of lines that it touches are counted), many photons ionise space in an area that partially covers several pixels, causing the charge pulse to be split and detected by several neighbouring pulse height analysers. This leads to under-reporting of the photon energy and over-reporting of the number of photons.

A solution to the problem of charge spreading or sharing is to detect when neighbouring pixels receive a pulse in the same short time interval, using coincidence detection methods. It is possible to design electronic circuits that sum such coincident pulses, and steer the total towards just one pixel. This is the "winner take all" method, implemented in a new version, version 3, of the advanced influential photon counting chip family, Medipix. Hence the term "photon processing", which reflects the fact that communication between pixels is used to recover the true photon count and energy.

2.7 Photon counting

The major CT manufacturers have developed variations of a technique that allows two x-ray energies to be measured: Dual Energy CT (DECT). The leading system is brutally simple: it has two tubes and two detectors operating simultaneously. This method, developed by Siemens, has some disadvantages, but is a commercial success. In another variation, developed and marketed by GE, the x-ray tube voltage is switched between two values in order to broadcast beams with different spectral profiles. An experimental system from Philips uses two layers of detectors, one below the other. The lower layer receives a filtered version of what the upper layer measures, with few low energy photons passing through to be detected. Once again, this leads to a distinctive spectral profile. It is possible, using the known differences in spectra, to derive useful information about energy specific attenuation at various regions in the object.

Recent advances in radiation detection, largely coming out of high energy physics research, have brought photon counting methods into the world of x-ray imaging.

The electronic processing of charge pulses caused by ionising radiation such as alpha and beta particles, and x-ray and gamma ray photons, was developed by such workers as Charles Wynne-Williams in Rutherford's laboratory in the later 1920s and 1930s. Wynne-Williams invented the first scaler or electronic counter (Wynne-Williams, 1932); his fundamental circuit, which used a gas-filled valve known as the thyratron, occurs in transistor form (MOSFET) in present-day photon counting x-ray detector devices. At that time, radiation detectors used gas discharge tubes (Geiger-Muller). Their bulk limited their spatial resolution and count rate.

A promising technique to count individual x-ray photons, and to measure their energy, has been in development now for over twenty years. The photon counting detector combines the fine spatial resolution and low electrical noise of tiny solid state detectors. These pixels distinguish the pulses of charge pairs, electrons and holes, caused by each x-ray photon in a semiconductor. Silicon, germanium, gallium arsenide and cadmium telluride are commonly used nowadays. The first such detector, using a single crystal of silver chloride, was built by van Heerden in The Netherlands in 1943. He referred to research done by George Jaffe who, in the 1930s, worked out the theory of ionisation by energetic particles and photons in solids and in gases.

There were problems (Hofstadter, 1950), in particular the build up of space charge or polarisation, which limited the usefulness of crystal detectors in high energy physics until the 1950s. Around that time the boom in semiconductor applications, resulting from invention of transistors (Shockley et al.), brought crystals of germanium and silicon of a previous unachievable purity (Gordon Teal). Germanium has a higher atomic number than silicon and has excellent properties for ionisation detection. However, it has to be operated at cryogenic temperatures to avoid leakage current caused by thermally excited electrons at room temperature. Silicon can be used in many circumstances due to the high purity attainable. Other materials in use are gallium arsenide and cadmium telluride, which again are more effective than silicon due to their higher density and thus higher stopping power.

Sensor development for the Large Hadron Collider, begun in earnest in the 1990s, led to the availability for wide-scale research and commercial applications of a general purpose, hybrid, 2D pixel, photon counting radiation detector in 1998. The original photon counting chip, PCC, later known as Medipix1 (see chapter 3) had 4096 (64 rows and 64 columns) pixels 170 μm square, and was used in a range of applications including x-ray imaging. Its successor, Medipix2, had 65536 (256 rows and 256 columns) pixels 55 μm square, and was later enhanced with Wilkinson counter functions in the Timepix variant. The first generations of Medipix were affected, due to their relatively small pixel dimensions, by loss of spectral accuracy due to charge sharing between pixels. The third generation Medipix3, for which a prototype was released in 2006 and the first design completed in 2008, has inter-pixel communication circuitry. Coincidence detection with winner-take-all arbitration combines photon charge pulses from simultaneous neighbouring events into one aggregated pulse. This technique of charge summing is also termed Photon Processing. The MARS project does research and development, using Medipix chips for x-ray imaging, in order to make a CT scanner for preclinical use and to explore the possibilities of CT with spectral sensitivity. Initiated several years ago to foster technology for export, the MARS project is a joint New Zealand government and commercially funded effort to develop a CT scanner that uses x-ray photon energy information to advance the state of the art in biomedical CT.

2.8 The energy dimension of CT

CT first became known for starting from a series of one-dimensional x-ray projections and using mathematical algorithms running on a computer to calculate and display the two-dimensional cross section of a living person's brain, to "see inside their head". With increasing speed and computing power, it is now routine to capture many "slices" of a person and present the many two-dimensional images to give various views of the three-dimensional anatomy. CT scanners are so fast that it is possible to take a series of observations over time, for example, of a beating heart, and to show dynamic changes in the moving organ.

Energy-related attenuation measurements provide a new dimension in the information readable from CT images. Dual energy CT is a reasonable approach, though there are compromises involved because it uses wide and overlapping energy "bins". The possibilities of multi-bin narrow-band high-speed spectral imaging are yet to be fully realised, but they include the following benefits:

ELIMINATION OF BEAM HARDENING The term "beam hardening" describes the relatively steep drop-off in intensity of soft x-rays as they pass through matter. Since this attenuation is proportional to the length of the intersection of the beam with the material, it causes greater drop off in "thick" sections than in thin. The effect is a distortion in the calculated linear attentuation coefficients during CT reconstruction. With energy-resolving detectors, the drop-off is correctly associated with the "bin" of low-energy photons and no distortion occurs.

HIGHER SIGNAL TO NOISE RATIO Small pixels allow highly sensitive amplifiers with relatively high signal to noise ratio despite the tiny pulse from an individual photon.

NANOPARTICLES AND FUNCTIONAL IMAGING Contrast media are widely used in CT, with new methods based on "nanoparticles" (NP) developing rapidly. By measuring the attenuation in narrow energy ranges, the K-edges of various elements (such as iodine, gadolinium, bismuth or gold) can be tested for the presence, location and concentration of those elements during a single exposure. Functional imaging, in which elemental nanoparticles are attached to antibodies for specific tissue - such as cancer cells - is an exciting new possibility. Several NP element labels could be used simultaneously to locate in-vivo processes in space and time. Spatial resolution would be much higher than is possible with positron emission tomography (PET or SPECT), another functional imaging method.

CONTRAST IMPROVEMENT For a given photon flux, the high sensitivity of photon counting detectors gives improved contrast. It is also possible to reject lower energy photons caused by Compton scatter and fluorescence, reducing the need for an anti-scatter grid.

TISSUE TYPE DISCRIMINATION With the knowledge that elemental concentrations can be measured by the K-edge mechanism, promising research is being done into the distribution of elements such as calcium and iron in atherosclerotic plaque. Another research project is to find methods of discriminating between benign and malignant breast cancer, using variations in calcification known to occur in different kinds of breast lump.

In summary, the above benefits lead to better diagnosis, while their combined effect also leads to dose reduction - a major need in a society where the increasing use of CT tends to increase the average exposure to radiation of each person.

Chapter 3

Medipix and the MARS Camera

Contents

The MARS camera, which is designed to be a vehicle for the Medipix photon processing chip, is a key part of the MARS CT scanner.

The next three sections are an introduction to Medipix and some existing products designed around this radiation imaging device. More detail about Medipix - its physical makeup, electronics, functions and operating experience - are presented in chapter 4. Following on from the very brief mention of other Medipix readouts and associated management software, section 3.4 outlines factors influencing the camera design. I identify the components of the MARS camera that support Medipix - electronics, mechanical, firmware and application programming interface - and explain the rationale for them. Section 3.5 provides some background to the camera development process. More details about the camera hardware, firmware and software are presented in chapters 5, 6 and 7.

3.1 CERN, the LHC, and Medipix

Heijne (2001) comprehensively reviewed the development of segmented semiconductor radiation detectors for particle physics. In the late 1980's there was a rapid evolution of integrated circuit manufacturing technology. Decisions were impending about building two new large scale colliders for high energy physics

(HEP): the Large Hadron Collider (LHC) in Europe and the Superconducting Super Collider (SSC) in the United States. While microstrip detectors, based on checkerboard-like arrays of electrodes deposited on both sides of silicon detectors, were the mainstream tracking devices, these large scale projects spurred the development of 2D pixel detectors for tracking. Eventually the SSC project was cancelled due to a lack of government funding. However, it was agreed in Europe that the LHC at CERN would be built, using the 27 km tunnel that housed the Large Electron Positron collider, LEP. The LHC has been at the heart of much of the development of novel radiation detectors from the beginning of the 1990's. Medipix is one of the best known of the spin-offs of these developments. Other 2D detectors developed since then in Europe include Pilatus, XPAD, MPEC (later CIX), PIXIE (now PIXIRAD) and DIXI.

PCC OR MEDIPIX1, A PHOTON COUNTING CHIP Technology transfer, the marketing and the diffusion of high technology into the public arena, is an opportunity and a necessity for CERN. Already in 1989, the principle of extending particle tracking detectors with scalers (counters) to allow imaging was discussed in Campbell et al. (1989). The photon counting chip (PCC), which came to be known as Medipix (later referred to as Medipix1), was announced by Campbell et al. (1998). Medipix was the name given to the project by the founders: CERN, University of Freiburg, University of Glasgow, and INFN in Naples and Pisa.

The Medipix1 application specific integrated circuit (ASIC) contains a 64 $\times$ 64 matrix of square pixels of 170 μm on a side. There are 4,096 pixels in total. It is built in complementary metal oxide semiconductor (CMOS) and designed, as the pixel processing part of a hybrid radiation detector, to be bump-bonded to a 1 cm^2 semiconductor sensor matrix. Each pixel has a preamplifier, discriminator, and a 15-bit counter. A 3-bit threshold adjustment DAC for each pixel is used to correct random variations in the discriminator threshold. The first sensor semiconductor bonded to Medipix1 was GaAs. Bettina Mikulec's PhD thesis (Mikulec, 2000) provides extensive details on the principles, modelling and testing of Medipix1 with GaAs. Figure 3.1 is a cross sectional diagram of a Medipix sensor pixel.

MEDIPIX2, MXR AND TIMEPIX The next generation to be developed, which had significant improvements due to advances in manufacturing technology, was Medipix2 (Llopart et al., 2002). Using a smaller line size in the CMOS ASIC of 0.25 μm the designers were able to fit 500 transistors into each pixel. It had a 256 $\times$ 256 array of square pixels, 55 μm on a side, giving a sensitive area of 2 mm^2. Each pixel had its own leakage compensation circuit and allowed charge pulses of both polarities. There were two comparators, allowing a "windowed" energy threshold. The counter was a 13-bit linear feedback shift register (LFSR). It can be read out with a high speed serial interface, or with a 32-bit parallel bus.

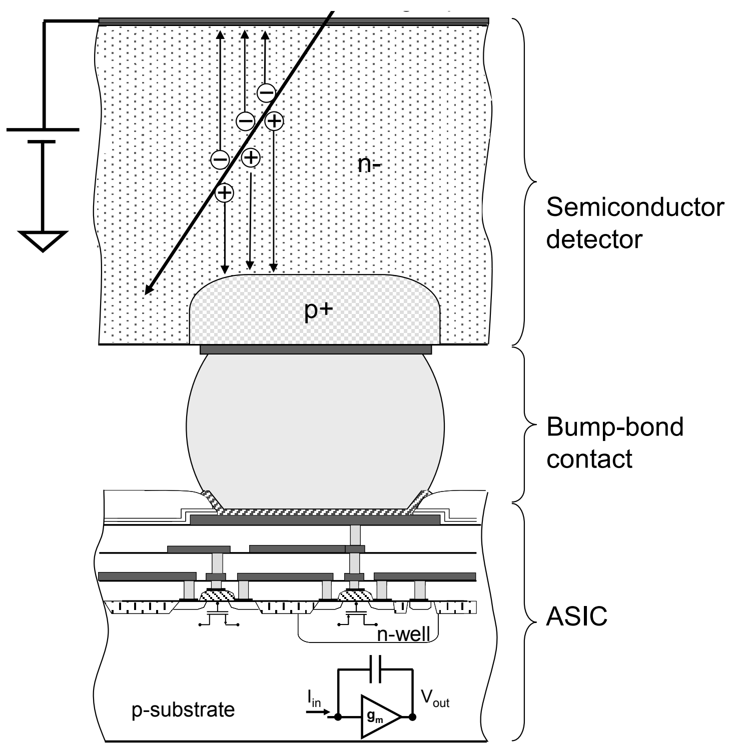

Figure 3.1: Cross section of a Medipix pixel. A photon is depicted entering obliquely into the semiconductor sensor layer, which has a reverse bias voltage applied to its diode structure. Clouds of electrons and holes are created due to ionisation by the energetic photon. As the clouds move under the influence of the electric field, they induce pulses in the electrodes. The lower electrode, connected by the conductive bump-bond, transfers the pulse to the charge sensitive amplifier and pulse counting circuit in the application specific integrated circuit or ASIC (Ballabriga Sune, 2009).

In 2004 the "MXR" version of Medipix2 was released. It is an improved version with better DAC stability, greater radiation hardness and a 14-bit LFSR. The MARS camera supports MXR. More information appears in chapter 4.

Based on Medipix2 but adding powerful event timing functions, Timepix was announced next (Llopart et al., 2007). It omitted one of the two comparators, but added the ability to count pulses from an external clock of up to 100 MHz to measure the arrival time, or the time over threshold (TOT), of a pulse. TOT is a form of multi-bit analogue to digital conversion, similar to the method used in a Wilkinson counter (the Wilkinson counter was the first electronic multi-channel analyser). Medipix1 and Medipix2 provide 1 bit of pulse height information. The Timepix threshold equalisation DAC is 4-bit, to improve the resolution of threshold adjustment. The MARS camera firmware does not support Timepix.

MEDIPIX3, CHARGE SUMMING AND SPECTROSCOPY A photon is detected from the pulse of charge that is created when it ionises atoms in the semiconductor sensor crystal. A cascade of ionisations occurs in a small volume in the sensor, creating a three dimensional cloud of electron/hole pairs. In silicon, one pair is created for each 3.6 eV of photon energy, so a 36 keV photon will generate 10,000 charge pairs. In the presence of an electric field applied across the crystal through conductive electrodes (about 100 V with silicon, up to 500 V with cadmium telluride), the electrons and holes travel to oppposite ends of the field and induce a pulse in the electrodes. The size of the "charge cloud", and its position relative to the pixel boundaries, means that more than one pixel may receive a share of the pulse induced by the charge cloud. Photon energy measurement depends on the pulse size; this pulse sharing causes erroneous detection of several low energy photons rather than one photon with the total energy that has been shared.

When the shift to 55 μm pixels was made between Medipix1 and Medipix2, the problem of charge sharing was foreseen. The effect is well known from simulation and from observations with Medipix2.

Medipix3 is designed to overcome the charge sharing problem. It uses analog summing circuits and coincidence detection to implement a "winner takes all" algorithm for pixels in groups of four. A prototype version with 8 $\times$ 8 pixels was built as a testbed for the charge summing design (Ballabriga et al., 2006). Design and manufacture of the full version of Medipix3 was delayed by unforeseen complications (Ballabriga et al., 2011), although a working version was available in early 2010. The MARS camera supports Medipix3. More information about the chip appears in chapter 4.

Medipix3 has several other features of interest. It has two comparators and two counters per pixel. The counters can be varied in depth from two 1-bit, 4-bit, 12-bit counters, to one 24-bit counter. Spectroscopic mode allows pixels to be combined into groups of four "super pixels" of 110 μm on a side by omitting three of the four bump bonds between sensor and ASIC. The comparators and counters of the four pixels can be switched to operate in parallel to provide eight simultaneous thresholds. The charge summing logic can be extended to work with the super pixels. Simultaneous read/write mode allows one counter to operate while its pair is read out, allowing zero dead time image taking.

APPLICATIONS OF MEDIPIX Members of the Medipix2 Collaboration, formed in 1999, have applied Medipix2 and Timepix in a wide variety of areas. Michael Campbell, the design leader for Medipix from the beginning, reviewed ten years of the Collaboration and its achievements (Campbell, 2011). The MARS project has access to many of the Medipix2 Collaboration's results, including a commercial license to its ASICs.

3.2 Readouts

From the beginning, Medipix chips have depended on users to develop their own electronic infrastructure to provide power, control and communication. Two institutions developed commercial hardware and software and made these available to other Medipix users in the collaboration. Other organisations have developed in-house equipment, but these are not generally available.

NIKHEF MUROS The Amsterdam based Netherlands Institute for High Energy Physics, NIKHEF, has developed two generations of a readout system. The MARS project has obtained both versions, known as Muros and Muros2 (Bello et al., 2003).

IEAP USB The Institute of Experimental and Applied Physics (IEAP) at Charles Technical University (CTU) in Prague developed a compact USB device that combines all the essential functions for a silicon Medipix chip in a handheld unit (Vykydal et al., 2006).

3.3 Management software

MEDISOFT4 Developed at the University of Naples, and INFN Naples, Medisoft4 (Conti et al., 2003) is a Windows program based on LabWindows (National Instruments). It was developed in coordination with NIKHEF for the Muros2 readout system.

PIXELMAN Pixelman (Holy et al., 2006) was designed at IEAP. As well as their USB readout, Pixelman also works with Muros2.

3.4 Camera strategy

SUPPORTED MEDIPIX VERSIONS Medipix3 is the chip for which the MARS project was waiting. The University of Canterbury is a member of the Medipix3 collaboration, and MARS Bioimaging Ltd (MBI) was established to market CT systems based on the unique features of Medipix3. But the chip was very late to arrive; the first assemblies capable of x-ray imaging did not become available to the MARS project until the beginning of 2010. In the interim, access was obtained to Medipix2 chips - MXR and Timepix - and these were used for initial project work. The MARS Camera (Figure 3.2) was designed to support MXR because this was available at a time when Medipix3 was not ready. Support for Timepix is included in the camera hardware, but the firmware does not currently work with it.

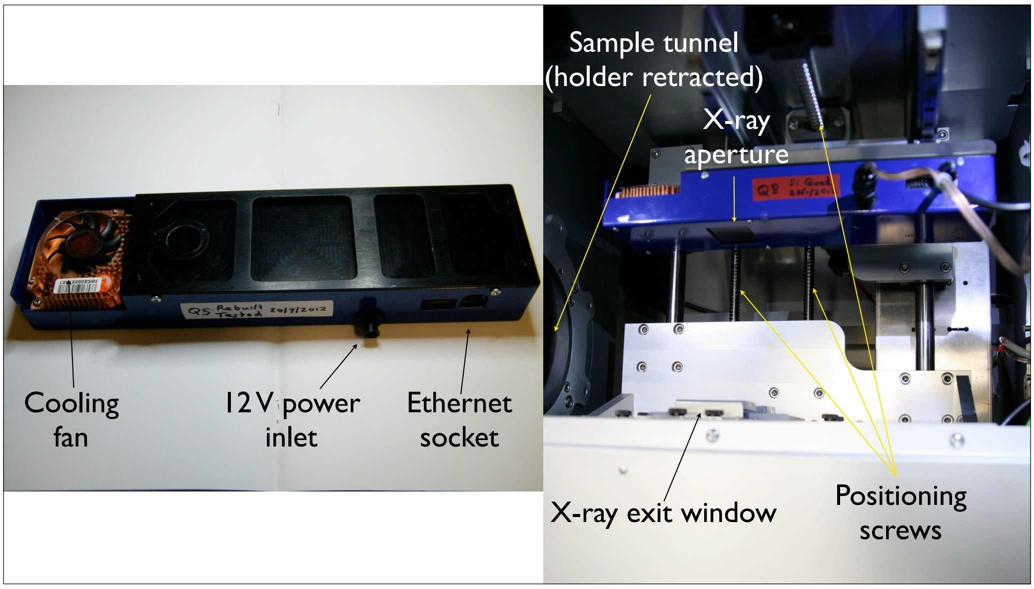

Figure 3.2: The MARS Camera. *Left* External view. *Right* Installed in a MARS CT scanner.

CHIP CARRIERS Medipix is "naked", without the usual plastic or ceramic housing to protect the raw chip from physical disturbance, moisture, and other hazards. Consequently there are no pins or leads with which it can be directly soldered to a circuit board. Instead it has a row of pads by which it can be attached by wire bonding. Fine wires, of diameter from 17 to 25 μm, are ultrasonically welded to the pads and to traces on a printed circuit board (pcb). These pcbs are referred to from here onwards as Medipix chip carriers. Many chip carriers have been designed by various collaboration members, including MARS. They hold from one to six chips and use various connectors; details, including images, can be found in section 5.3 in chapter 5.

POWER SUPPLIES Medipix has analog amplifier circuits which are sensitive to very small signals: the charge pulses resulting from a single photon being absorbed in a sensor pixel. It also has digital components which by their nature generate electrical noise. As a basic preventative measure, the power supplies for these two sides are physically separated on the chip. In addition, the external communication channels that use LVDS also have a separate power supply. Medipix3 has a fourth supply, only used when the identifying fuses are to be programmed.

The MARS camera provides four power supplies to Medipix, three of which have programmable voltages to cope with the different requirements of Medipix2 and Medipix3.

Exposure to x-rays gradually increases the amount of current drawn by Medipix2 chips due to increased leakage of transistors. This can be compensated for by slightly increasing the power supply voltage. In order to detect the increase in current, the camera includes both current and voltage sensors in the key Medipix power supplies.

HIGH VOLTAGE BIAS SUPPLY Medipix chips since version 2 are able to operate with charge pulses of positive or negative polarity (Medipix1 required positive pulses). The choice polarity depends on the sensor semiconductor material. Silicon and gallium arsenide are most effective when the common electrode is positive, which leads to positive-going charge pulses as holes travel to the pixel electrode. Cadmium telluride is more effective when counting electrons, due to low hole mobility.

The absolute bias voltage also needs to be adapted to the sensor material, depending on the thickness of the layer and on the semiconductor material.

With cadmium telluride sensors there is a high “inrush” current when the bias supply is switched on. The supply has to be robust enough to be stable despite this initial surge.

The design of the high voltage supply board in the revision C, 2011 version of the MARS camera was determined by the above needs. The supply is electrically isolated to allow either its positive or its negative output to be safely connected to system ground. The supply is programmable in the range of 100 to 500 volts, covering the requirements of Si, GaAs and CdTe. It has a substantial current sourcing ability, around 2 mA.

Further details, including a photograph, are found in section 5.2 in chapter 5.

COOLING, SHIELDING AND INSULATION The electrical properties of cadmium telluride are highly sensitive to temperature; operating temperatures above 30 degrees C are undesirable. Medipix3 chips (v3.0) are also sensitive to overheating. A Peltier cooling system was added in 2010. Heat conducting metal plates surround an enclosed air space, and form a heat sink to thermal vias beind the Medipix ASIC in the chip carrier. A small fan removes heat from the high temperature side of the Peltier device. An enclosing air space for the Medipix3 chip is formed by an acetal mounting block that also provides mechanical protection of the Medipix chips and is light-tight (photons in the visible wavelengths generate leakage current in the sensor layer).

Radiation shielding and high voltage insulation are included on the front surface of the camera case, that is the side that faces the x-ray tube and which has a rectangular x-ray beam aperture. Lead shielding protects the motherboard from x-rays, and mylar insulation reduces the chance of flash-over from components on the high voltage board.

See section 5.4 in chapter 5 for further details.

CAMERA DC POWER INPUT A combination of constraints set by the high voltage board, Peltier device and cooling fan led to a decision to use 12 volts as the fixed camera supply voltage. The original design was intended to work over a wide range of DC input voltages, but this was impractical. For example, the power control transistor for the Peltier device has to dissipate too much power when the supply voltage is above 12 V.

FIELD PROGRAMMABLE GATE ARRAY An FPGA allows optimisation and fine tuning of the low level Medipix command and communication interfaces without requiring any change to the motherboard electronic design. Its ability to implement a “soft” microprocessor (the Nios2), random access memory (DDR) controller and Gigabit Ethernet controller makes it a viable alternative to a standalone microprocessor.

SHUTTER TIME RESOLUTION The FPGA includes logic to generate shutter times to Medipix with a resolution of microseconds. This option has not been used in the current firmware but may be enabled in the future. Instead, a software timer is used. To allow operation of several cameras as a unit, there is a software accessible synchronising input on the diagnostic RS232 connector.

DACS AND ADC The ability of the Medipix chips to connect any one of the chip DACs for external measurement is a valuable tool for testing and possibly for fine-tuning of chip performance. The ability to supply an external analog voltage to override one of the chip DACs is also a test tool, and provides an emergency repair in case one of the DACs does not function (as occurred in Medipix3 v3.0)

LOW AND HIGH LEVEL MEDIPIX CONTROL It would have been possible to locate most of the Medipix low level transaction control in the MARS camera firmware. If this was done, the camera would look like a black box to the external PC, which would not “know” that Medipix chips are at the heart of the camera. For example, the PC might ask for a threshold voltage (or even for a threshold energy), a shutter time, and for an exposure to be taken. It would then receive a binary file, perhaps already in a standard image format.

Instead, the low level management of Medipix has been shifted largely to the PC. The Medipix2 fast shift register (FSR) has its individual bits set and cleared on the PC in order to control the chip DACs. The Medipix3 OMR and DAC registers are managed in a similar way. The serialisation and deserialisation of the matrix data is also done on the PC, leaving the camera firmware with the job of physically transferring register and matrix data bits onto and off the chips.

One reason for assigning the main responsibility to the PC is that it has a faster processor than the FPGA-based microcontroller. Another advantage is that complicated workarounds for Medipix problems can be dealt with in a flexible way.

Despite the PC advantage, there are some Medipix features that are handled by the camera firmware. For example, Medipix3 v3.0 workarounds to do with counter matrix sequencing are located in the firmware to give reasonable performance.

NETWORK SPEED AND PROTOCOL The use of Ethernet made it easy to choose IP and UDP as networking protocols. This is a good choice to give the flexibility in connecting PCs to the camera. For example, each of Linux, Mac OSX and Microsoft Windows can easily be operated with the MARS camera.

3.5 Camera development

The decision to make a MARS camera was taken in September 2008. The initial design, undertaken by Marcus Clyne of Christchurch firm ILR, used an FPGA demonstration motherboard from Altera. It included a high density 180-pin Samtec socket. The prototype MARS camera readout board was built with a plug to fit the Samtec connector. It had its own Samtec socket, for which adaptor boards were designed for the CERN Medipix2 and Medipix3 chip carrier boards. The CERN boards use 68-pin SCSI connectors. Connection to a Medipix2 chip was initially made using a bulky round profile SCSI cable. Flat SCSI ribbon cables and a PCB mounted male SCSI connector were sourced from the United States.

The prototype board was designed with several power supplies as expected by Medipix, but for initial testing the digital and analog supplies were joined together. This led to a problem which was resolved only a couple of days before I travelled to Europe to attend a Medipix meeting in Grenoble. The problem with joining digital and analog supplies was that the Medipix DACs did not work correctly. I was unable to make the threshold DACs travel through their full range. I was still able to obtain some images, but did not feel that I was in control of the system. Nick Cook of the Canterbury District Health Board Medipix Physics department is the Medipix expert who pointed out the problem. It was easily fixed, since separate power supply circuits had been designed into the hardware; they simply required components to be fitted by Marcus.

Altera's demo motherboard contained numerous chips in support of the FPGA (EPCS25, Cyclone III). It had a USB to JTAG interface on board, meaning that external debugging could be done without a "USB Blaster" by connecting the PC directly via a USB cable. There was a flash EPROM to hold the FPGA configuration and the camera firmware. The FPGA configuration contained several complex "virtual" components, including one made of commercially obtained logic, from IFI in Germany, to implement the MAC layer of Gigabit Ethernet. Other components on the FPGA configuration were a DDR RAM controller , and most significantly, the logic of a "soft" microprocessor, the Nios2. Nios2 is a 32-bit RISC processor, clocked at 50 MHz on the MARS motherboard. Altera supply a C compiler for Nios2, built from the invaluable (and free) *gcc* open source compiler kitset. The program to run on this CPU, the camera firmware, is also installed on the flash memory. The flash memory, with FPGA configuration and the camera firmware, is loaded via the USB-JTAG interface using a flash-programming utility program on the PC. This program is supplied by Altera, and is able to be used both from the Nios2 software development kit GUI, and from a *bash* shell command line.

On the prototype MARS board, in addition to the SCSI interface, there was a Gigabit Ethernet PHYTER chip and RJ45 jack. The PHYTER implements the low level electrical and complex serial coding layers of Gigabit Ethernet. It connects via an 8-bit bus and control lines to the FPGA, on which the IFI MAC logic provides an interface for software running on the Nios2 microprocessor.

After the combination of Altera board and prototype motherboard had been used to develop and prove the basic Medipix communication functions, a new MARS motherboard was designed by ILR that incorporated the essential Altera components. The main omission is the USB-JTAG interface. Instead of connecting a PC directly for debugging and firmware loading, an external "USB-Blaster" device has to be used. It connects to a JTAG header on the motherboard.

The MARS motherboard design also added components to implement the various functions that have been identified in this chapter, such as the programmable power supplies, interfaces for up to six Medipix chips, and a connector for communication with the high voltage board. This motherboard is now in its third revision, revision C. Alongside it, the high voltage board is also at revision C. Details of these circuit boards are found in chapter 5.

Figure 3.3 is a block diagram showing a view of the camera architecture.

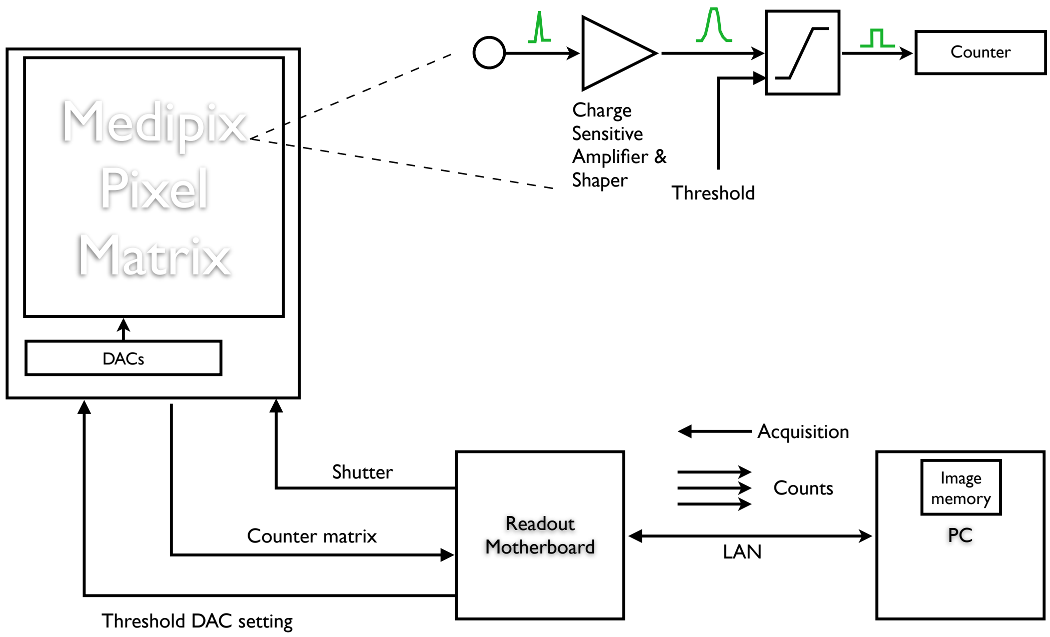

Figure 3.3: Block diagram showing the connections and flow of data between Medipix and the MARS Camera and PC. The effect of a photon charge pulse is depicted for a representative pixel.

Chapter 4

Medipix reference information

Contents

This chapter is a survey of the key facts about Medipix that I needed to know, or, in the case of the section on Pragmatics, that I and others learned, by working with the MXR and Medipix3. My primary sources of information are two PhD theses (Llopart Cudie, 2007; Ballabriga Sune, 2009), and the MXR and Medipix3 user manuals (Llopart, 2006; Ballabriga et al., 2009).

The structure, sequence and organisation of this chapter was created as a result of my efforts to produce the working MARS camera. Medipix is a complex device that can be seen from several different perspectives, and my experience with the user manuals was not an easy one. At one stage, early in my research, I was tempted to write my own version of a user manual. While the contents of this chapter do not pretend to be a manual, I believe that the chapter will assist a newcomer to understand the Medipix chip.

The main focus of the chapter is on Medipix3. However, the Medipix2 MXR is also discussed.

There are four sections. Section 4.1 is a brief overview of the physical Medipix device, which is in fact two separate semiconductor devices - the sensor layer, and the pulse analysing ASIC (Application Specific Integrated Circuit) bonded face to face. That is, it is a "hybrid" detector assembled using the flip-chip method. The second section, 4.2, walks through the electronics of the detector, starting with an individual pixel at the sensor layer and passing by the "front-end circuits" that amplify and shape charge pulses from the sensor layer. Pixel processing continues with the discriminator, or threshold detector, and terminates at the counters. The pixel configuration register is mentioned. Finally, the Medipix3 charge summing feature is described from the pixel point of view. The final part of this section looks at electronic aspects of the chip as a whole, including the DACs and external interface. Moving on, section 4.3 is about the operation and control of Medipix, in other words about the chip functions. It discusses digital communication, the commands and actions, and the configurable settings. Finally, section 4.4 is about practical knowledge that I (and others) have gained about the operation of Medipix devices.

4.1 The physical device

Figure 4.1 is a close-up photo of a Medipix3 detector mounted on the CERN chip carrier. The Medipix detector is assembled from two integrated circuits. The upper sensor circuit is an array of pixels formed by plating electrodes on to a slice of semiconductor material, forming a two dimensional array of radiation sensitive diodes. The lower ASIC contains two sets of electronic circuits. The largest part is a set of pulse analysing circuits, one per pixel. The remaining part is a set of global DACs and some other support circuits. The sensor and ASIC are bonded together by an array of conductive bumps. In some cases the bonding is achieved by heat alone; in other cases, for heat-sensitive devices, a low temperature compression technique is used. The process, known as "flip-chip", was invented by IBM in the early 1960s to increase the density of circuitry in mainframe computers (Miller, 1969). The technique has been licensed by IBM to many users. This device is known as a hybrid detector due to its two part design.

The main advantage of the hybrid design is that the pixel processing ASIC can be manufactured using processes independent of the detector semiconductor. Another advantage is that the fill-factor of the detector is 100 %, since there are no electronic circuit components using part of the radiation sensitive area. By omitting a proportion of the bump bonds it is possible to assemble a detector with pixels that are a multiple of the standard pixel pitch in size. If this is done, it is possible to use Medipix3's spectroscopic mode. Each pixel is then a "super pixel" with a pitch of 110 μm and an eight channel pulse height analyser.

More details about the two Medipix circuits are given in the following subsections.

4.1.1 Detector layer

The upper semiconductor layer is the radiation detector. It is made from a single crystal of semiconducting material, sliced and polished to a thickness that ranges from 300 to 1000 μm or more. The detector upper surface is plated with a very

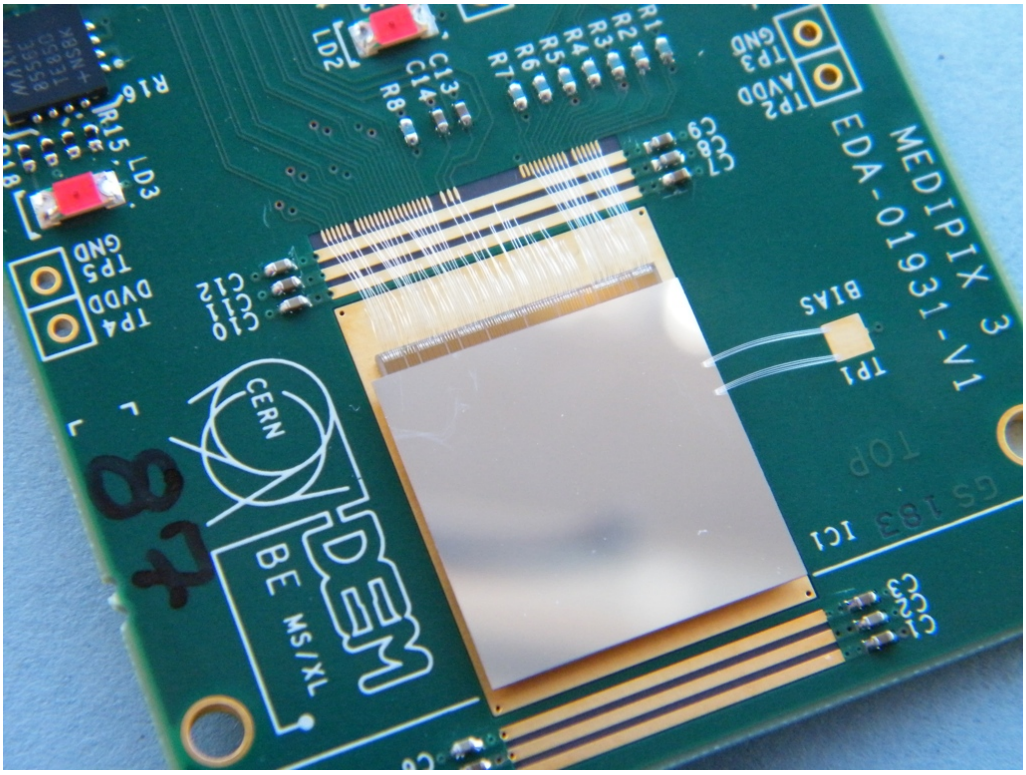

Figure 4.1: Photo of a Medipix3 chip mounted on the CERN chip carrier. The ASIC layer is just visible at the top edge of the square assembly where the wire bonds connect the lower chip to the printed circuit board. The high voltage bias supply is connected to the upper sensor layer on the right.

thin metal electrode: aluminium for silicon detectors; platinum is used with cadmium telluride. The lower surface has a regular array of electrodes spaced 55 μm apart. Between the metal electrodes and the semiconductor material there may be deposits of dopant that contribute to the diode structure of the detector. The effect of the array of electrodes is to create “pixels”: individual picture elements that are separate, contiguous, radiation sensitive picture elements.

After a hybrid detector has been assembled by the flip-chip method and mounted on a chip carrier, a high voltage bias wire is bonded to the detector layer upper surface. The polarity of the voltage source is chosen to reverse-bias the detector pixel diodes. Silicon is normally used with a positive upper electrode, while CdTe is negative. The other side of the high voltage bias is connected to the chip carrier ground, which is shared by the various ground inputs to the hybrid detector.

For some sensor materials such as cadmium telluride there is a conductive grounded "guard ring" around the edges of the inner surface. The effects of the guard ring are to reduce leakage current, and to retain straight electric field lines in pixels along the edges of the detector (Nakazawa et al., 2004).

4.1.2 Pixel processing ASIC

The lower circuit in the Medipix hybrid detector contains the pixel processing electronics in the form of an application specific integrated circuit (ASIC). It contains the pulse analysing and counting circuit for each pixel on the detector. Matching the layout of the detector pixel electrodes, these circuits are arranged in a square array with a 55 μm pitch. The MXR and Medipix3 ASICs are manufactured using the CMOS process, a low power technology. The MXR has a line width of 0.250 μm, and Medipix3 has 0.130 μm.

A set of digital to analog convertors and other support circuits are built into a narrow rectangular section along one edge of the ASIC, adjacent to the matrix of pixel circuits. On the other side of this segment, which is known as the "periphery", is a set of metallised bond pads. These pads, which are used to carry power, control and communication signals, have fine wires ultrasonically bonded to them to connect the ASIC to printed circuit traces on the chip carrier. Medipix3 has an optional second set of bond pads on the opposite edge of the ASIC. These can be cut off during chip dicing, and are used in cases where the most consistent power supply voltage is needed. Medipix3 also has a set of through silicon vias (TSV), conductive channels that pass from the lower surface of the chip to the active circuitry. These can be used to eliminate both sets of bond pads to minimise the amount of space covered by a detector, allowing the largest possible area of active sensors. The vias are under test and development by several members of the Medipix3 collaboration.

The MXR, and a Medipix3 with a single row of bond pads, is capable of being "tiled" into two rows of chips butted against each other on three of their four sides. "Quad" and "Hex" versions of both chip types have been produced. There is an area of oversized pixels along each matching edge: on the MXR Quad, these pixels are three times the normal width in the direction perpendicular to the edge: 165 μm. At the internal corners the pixels are three times the height and three times the width of a normal pixel.

4.2 Electronic design

Each pixel in Medipix includes a miniaturised implementation of a "nuclear amplifier chain" with a one or two channel pulse height analyser. The sensor pixel is equivalent to a semiconductor diode radiation detector. Almost all of the principles of semiconductor radiation detectors (Lutz, 1999) and nuclear particle detectors and electronics (Knoll, 1989; Grupen et al., 2008) are transferable to the understanding of the Medipix design. However, the charge summing system of Medipix3 is a significant innovation which employs ideas from neural network technology. Figure 4.2 shows a block diagram of the electronics in a Medipix3 pixel.

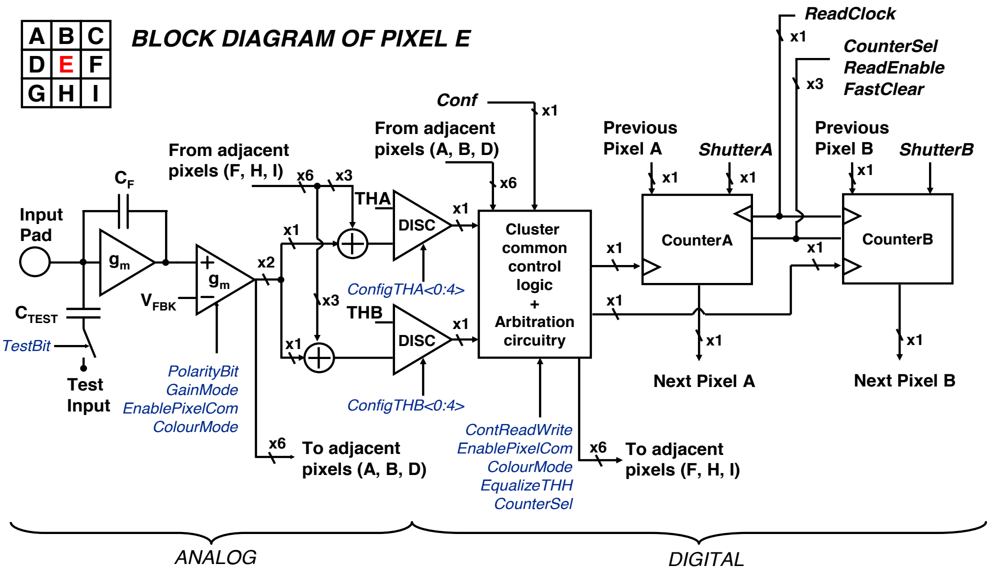

Figure 4.2: Block diagram of Medipix3 pixel electronics (Ballabriga et al., 2009)

Subsections 4.2.1 to 4.2.7 describe aspects of Medipix electronics that are common at the pixel level. The final two subsections, 4.2.8 and 4.2.9, describe electronic functions - the DACs and the external interface - that are “global”, or shared between all the pixels.

4.2.1 Radiation sensor

X-ray photons and fast moving charged particles interact with matter by breaking bonds between electrons and atoms, creating free, negatively charged electrons, and positive ions. In a solid such as a semiconductor, the ions are immobile, but the missing electrons create a virtual charge carrier termed a “hole”. If the photon or fast moving particle has enough energy, it will generate many thousands of electrons and holes. There are a number of ways in which we can detect the presence of these charge carriers. In an electric field, between measuring electrodes, they create a pulse of current that can be measured. The current is caused by the motion, forced by the electric field, of the negative electrons and positive charge carriers towards the oppositely charged electrodes.

Compared to a gas, a semiconductor, being solid, is enormously more effective as a detector of photons and charged particles, due to the much greater chance of an interaction in a solid (about 1000 times more dense than a gas). A semiconductor is also effective due to its useful electrical properties. In a diode the presence of a strong reverse bias voltage, opposite to the direction in which current is naturally able to pass, forces charge pairs to drift towards the electrodes. Because almost no current normally passes when a diode is reverse-biased, it is possible to connect an extremely sensitive amplifier, known as a charge sensitive amplifier (CSA), directly to the electrodes. If the charge pairs are in a strong electric field the pulse is of short duration, of the order of tens of nanoseconds. It is feasible for small amplifiers to respond completely to individual pulses, allowing a high rate of radiation events to be detected.

The number of charge pairs created in an ionising interaction is approximately linearly related to the energy of the photon or charged particle. By integrating, the charge current in the pulse from a detector, it is possible to obtain information about the energy of photons and charged particles. Energy information is obtained in one of two ways. The first way is to compare the size of a pulse with a test value, so that a trigger signal is passed to a counting circuit each time an incoming pulses exceeds this test or "threshold" value. The second way is to use an analog to digital convertor to convert the pulse height to its digital value, then use this value to index an array of counters and increment the counter whose index has been given. These techniques have been in use in electronic nuclear amplifiers since the early twentieth century and the method is known as "pulse height analysis".

Threshold detection, as done by Medipix, is used indirectly to measure the energy spectrum of x-ray photons. This is done by taking a series of observations of pulse counts at a series of different thresholds. By taking the difference in counts between adjacent thresholds, the shape of the pulse height spectrum, and the energy spectrum, can be calculated.

For research into nuclear radiation, and in high energy physics, knowledge of the energy of photons and charged particles is a basic requirement. Medipix provides threshold detection capability in a 2D array of pixels, tiny and dense enough to take an x-ray image with film-like resolution. It is fast enough to do so for every photon that creates a pulse in the small space of a pixel. In diagnostic radiology the ability to count photons and measure their energy is a new and barely explored tool. Implementing and exploring the expected benefits of energy spectral sensitivity to computed tomography is the purpose of the MARS project.

4.2.2 Charge sensitive amplifier

Krummenacher (1991) calculated and promoted the benefits of building the complex functions of a nuclear pulse height analyser into the space of each pixel of a segmented radiation detector. Electrical noise is normally a significant problem, because it competes with and masks the tiny charge pulses from a radiation detector. Krummenacher showed that the small circuits that can be built using the new technology of microminiature integrated circuits, with feature sizes of 1 μm or smaller, significantly reduce the amount of noise due to detector and amplifier capacitance. Taking advantage of miniaturisation, with many more transistors per pixel, it was possible to include pulse counters - and thus enable radiation imaging. Krummenacher described innovative circuit designs to take the best advantage of the space available for transistors in one pixel. His contribution has earned him the honour of having one of the key Medipix digital to analog convertors (DACs), the current (I) source `IKrum`, named after him.

Krummenacher's charge sensitive amplifier amplifies and integrates the charge pulse from a photon interaction. His design includes a mechanism to bypass the small but disruptive leakage current that occurs in a reverse biased diode. If leakage current is allowed to pass into the amplifier, it "saturates" the pulse integrating capacitor and prevents pulses from being detected. After a pulse has been integrated and passed through to the threshold detector, Krummenacher's mechanism also resets or clears the capacitor of charge, making it ready for the next incoming pulse.

In the first design, in Medipix1, only positive going charge pulses were able to be measured. This was a limitation, since one of the promising semiconductors for x-ray imaging, cadmium telluride, gives its best performance when biased to give negative going pulses. The Medipix2 and Medipix3 version of the CSA is able to handle pulses of both polarities.

ASSOCIATED GLOBAL DACS `Preamp` and `Ikrum` (or `IKrum`) are current reference DACs. `FBK`, `Cas` (in Medipix3) and `GND` are voltage references. `GND` sets the "virtual ground" level of the pixel electrode; its value is chosen to match the polarity of incoming pulses, according to the presence of a positive or negative high voltage bias. Positive bias causes holes to be counted; negative bias, used with cadmium telluride, counts electrons. `FBK` sets the the idle voltage level of the CSA output. Its value is also chosen depending on the incoming pulse polarity.

4.2.3 Shaper

The output of the CSA looks like a "step function", and its final amplitude is a measure of the size of the photon charge pulse. The best way for such a pulse to have its height measured is for it to be smoothed, and made as far as possible into a symmetrical shape. These functions are performed by the "Shaper" circuit, which uses active differentiating and integrating filtration to optimise the amplified pulse. Abnormal short pulses, caused by electrical noise, are suppressed. The inherent asymmetry of the step function, which causes a distortion from the ideal output pulse shape, is able to be tuned out using the process of pole zero compensation.

The Medipix2 MXR did not have room in each pixel for the transistors needed to provide a shaper circuit. It is possible to obtain some of the advantages of pulse shaping by tuning its CSA output through coordinated setting of the `Ikrum` and `Preamp` DACs.

ASSOCIATED GLOBAL DACS `Shaper` is a current reference. `RPZ` is a voltage reference that tunes the pole zero compensation transistor.

4.2.4 Discriminator

There are various ways to measure the height of an electrical pulse. In the early days of electrical nuclear pulse processing, an electromagnetic device known as a kick-sorter was used to bump metal balls by a force proportional to the pulse height - like a pinball machine. Different pulse heights caused the balls to be deposited at different places in a stack, allowing the pattern of pulse heights to be seen.

Another design, known as the Wilkinson counter, relies on an approximation, that the time during which a pulse is above threshold is proportional to the pulse height. The counter works by passing pulses from a fast clock source to the counter during the time that the pulse is above threshold. This is the method used in Timepix, the most recent version of Medipix2.

Already mentioned briefly, the modern multi-channel pulse height analyser has an analog to digital convertor (ADC) that converts the pulse height to a digital value. This number is used as the address of a counter in memory, and the counter is incremented. It is possible to count hundreds or thousands of different pulse heights, depending on the resolution of the ADC and the amount of memory available.

Medipix implements a one- or two-channel pulse height analyser in each pixel. It contains discriminator circuits that are triggered when the amplitude of a pulse exceeds an adjustable threshold. When the discriminator is triggered it causes a digital counter to be incremented. The Medipix2 MXR has two discriminators which perform a windowing operation: they only increment the counter if the incoming pulse exceeds one threshold and at the same time falls below a higher threshold. On the other hand, Medipix3 has two discriminators and two counters, providing two channels of pulse height analysis per pixel.

The discriminator threshold is set by the threshold DACs: `THL` and `THH` in the MXR, and `Threshold0...1` in the Medipix3. If the sensor is irradiated by trial sources with known narrow bands of photon energy, the relationship between threshold DAC value and photon energy is able to be established. Two different energies are needed for a linear fit.

DC OFFSETS AND EQUALISATION Unavoidable manufacturing variations in the electrical characteristics of the CSA, shaper and discriminator lead to random dispersion of the zero point of the Medipix discriminators. This is enough to reduce the accuracy of energy calibration. Medipix provides an adjustment for each pixel to correct for this offset error. In the MXR the adjustment is provided by a three bit DAC, which has eight possible values. In Medipix3 there is a higher resolution scheme. It has a four bit DAC per pixel for each of the two discriminators. The DAC can optionally have a global negative shift added to it, meaning that there are effectively five bits of adjustment per discriminator.

The process by which the pixel adjustment DACs are set is called equalisation, and the DACs are referred to as pixel equalisation DACs. There are several methods for performing equalisation. A simple method, requiring no external radiation source, depends upon the simplification that low-level electrical noise, inherent in every pixel, is usable as a standard signal. Setting the discriminator threshold into the (normally avoided) noise zone, the thresholds at which noise pulses start appearing, and then disappear, are taken to be constant across the chip and can be used to choose an appropriate offset correction to program into the equalisation DAC.

Another technique is to use a known mono-energetic radiation source to irradiate the sensor, and to adjust each pixel so that the count rates at a given threshold are equal. Radio-isotopes, fluorescing foils, and the peak energy from an x-ray tube are used as such an energy signal.

ASSOCIATED GLOBAL DACS The threshold DACs in the MXR are `THL` (the lower edge of the window) and `THH` (the upper edge). In the Medipix3, in its standard two-threshold mode, the thresholds are `Threshold0` and `Threshold1`.

In the MXR, `THS` sets the input current to the pixel equalisation DACs. In Medipix3, `DAC_pixel` sets the positive input current to the pixel equalisation DACs, while `ThresholdN` sets the (optional) negative current. `Disc`, and `Disc_LS` in Medipix3, are current references. `DelayN` adjusts the length of the output pulse in the MXR. `Delay` in Medipix3 is not documented, but probably performs a similar function.

4.2.5 Counters

The rate at which photons are detected by a pixel is a measure of the intensity of radiation at the pixel. If the charge pulses from a pixel can be counted during a time interval, the count is the brightness at that pixel. Reading out the counters from all the pixels and presenting them on a digital display creates an image of the radiation pattern falling on a detector. The same principle is used in a digital camera, except that the digital camera does not have a counter per pixel. Digital cameras use analog to digital conversion of a voltage stored for each pixel in the sensor. This is an integrated voltage and does not contain information about individual photon energies. Medipix has digital counters that show the number of single photons, selected according to their energy.

A digital pulse counter can be based on standard digital arithmetic circuits. A binary adder with a carry bit is easy to implement and exists in various forms in digital computers. There is a special requirement in Medipix, which is that there are 2^{16} pixels each with a counter, and these 65536 pixel counters have to be read out after an exposure has been taken. The natural way to read them is via "shift registers". A shift register is analogous to a conveyor belt, on which the bits of digital data are moved in a sequence to an end point at which they are transmitted to the outside world. Medipix, which has design constraints on the number of transistors used in a pixel, combines some of the functions of a counter with the functions of a shift register.

One way to combine a counter with a shift register is to use a circuit known as a "linear feedback shift register" (LFSR). An LFSR works by feeding the output of the shift register to its input, in logical combination with each incoming pulse. Depending on the feedback operation, the bits stored in an LFSR will pass through a series of patterns which are not numerically in sequence, but which can be decoded by a simple algorithm to determine their position in the sequence. The MXR uses this technique in a 14-bit shift register; it has 11,810 unique patterns (out of the 16,384 patterns that can be stored in a 14-bit register). By using an LFSR, it is easy in the MXR to transform the pixel counters from separate LFSR counters into a super-shift-register of daisy-chained 14-bit registers. They can be read out after an exposure is complete. The MXR has a single set of shift registers, the counter matrix. It has a total of 65536×14 bits, that is 917,504 bits.

The sequence of patterns generated by an LFSR has the appearance of randomness, sometimes referred to as a "pseudo random binary sequence" (PRBS). Occasionally the Medipix2 type counters are referred to as pseudorandom counters.

Medipix3 uses binary adders which count up from 0 to their maximum value. They are able to be combined into a long shift register to allow readout. Medipix3 has two complete sets of shift registers, known as counter matrices C0 and C1. They correspond to the two counters in each pixel. Each matrix has 65536×12 bits, that is 786,432 bits: a total of 1,572,864 bits in the combined matrices.

DYNAMIC RANGE The MXR can count up to 11,810 pulses. That is the maximum count, after which new pulses are ignored. Hence this count should be treated as an "overflow" value.

The Medipix3 counter size is programmable, and in the MARS camera they are set to 12 bits. The maximum value is 4095, which is treated as an overflow value since any pulses beyond this count are ignored.

COUNT RATE The MXR has been characterised at up to 10^6 pulses per second per pixel. Medipix3 has not been fully characterised. Preliminary results (Ballabriga Sune, 2009) indicate that its maximum count rate is less than that of the MXR when charge summing mode is enabled.

4.2.6 Pixel configuration register

Each pixel has programmable settings. The equalisation DACs have a programmable value, and there are some optional functions. These settings are stored in the pixel configuration register (PCR). The PCRs are loaded when the counter matrix is loaded. The MXR PCR is eight bits long: six bits for the two equalisation DACs, one bit to switch a pixel from active to inactive (the "mask" bit), and one bit to connect the test pulse input to the preamplifier.

The Medipix3 PCR is thirteen bits long: ten bits for each of the two equalisation DACs (including the negative offset bit), one mask bit, one test pulse bit, and one bit that selects low gain or high gain in the shaper circuit. To load the PCR both counter matrices, C0 and C1, must be loaded.

4.2.7 Medipix3 charge summing

Each x-ray photon that is absorbed in the Medipix sensor layer is annihilated, leaving a cloud of charge carriers - electrons, and the positively charged vacancies or "holes" from which the electrons have been separated. The number of charge carriers is approximately proportional to the energy of the photon. For example, in silicon at diagnostic x-ray energies, one electron-hole pair is created for each 3.6 eV of photon energy. The charge cloud from higher energy photons is comparable in size to the dimensions of a pixel, 55 μm on a side.

A consequence is that the charge pulse is often distributed amongst several pixels, up to four pixels (or even more) if the photon interaction occurred at a corner.

If a charge cloud less than 55 μm in diameter is deposited near a corner, up to four pixels may each receive a fractional charge pulse. In Medipix2, the total charge from such a photon will be incorrectly attributed to four lower energy photons that happened to arrive at the same moment in time. The effect of this is seen in an energy spectrum of a single-energy source: there is a "tail" of counts that extends from the low energy side of the true peak, all the way to the minimum energy measured. The tail is caused by the partial charge clouds generating small pulses, with a continuum of heights depending on the split across pixel boundaries. For photons of energy greater than 50 keV, the charge cloud diameter has been modelled to be greater than 150 μm and the cloud will be spread over many pixels.

[The description in the next paragraph is a paraphrase from parts of Rafa Ballabriga's PhD thesis (Ballabriga Sune, 2009). The real world performance of the CSM system in Medipix3 version 3.0 has been disappointing (Gimenez et al., 2011; Pennicard et al., 2011) and there are doubts as to whether the description accurately matches the system's actual behaviour. The CSM system was at the heart of a major redesign during which more than a year has elapsed, leading to version 3.2 of Medipix3, and we hope to see the results in the near future!]

Medipix3 can be configured to perform coincidence detection and charge summing at a "node" at the meeting point of each group of four pixels. When several pixels receive pulses at the same instant (within some nanoseconds of each other) the sum of the charge pulses is calculated. The pixel that had the highest proportion of charge is signalled to receive the total charge, while its neighbours are temporarily disabled. Only one photon event is recorded and the photon energy correctly recognised. The method of arbitration is known as a winner-take-all algorithm.

Charge summing is switched on using the option `EnablePixelCom` in the OMR register. The option name shows that communication between pixels occurs during charge summing.

4.2.8 Global DACs

DAC	Code B3-B0	Range	Bits	Mid range value	V/I	LSB size	Bits in FSR <LSB:MSB>
IKrum	1111	0-40nA	8	20nA ⇒ 1.497V	I	0.157nA	<3:10>
Disc	1011	0-1.67μA	8	840nA ⇒ 1.005V	I	6.57nA	<11:18>
Preamp	0111	0-2μA	8	1.0μA ⇒ 966.4mV	I	7.89nA	<19:26>
BuffAnalogA	0011	0-10.2μA	8	5.04μA ⇒ 924.1mV	I	39.4nA	<45:48><55:58>
BuffAnalogB	0100	0-391μA	8	197μA ⇒ 1.168V	I	1.54μA	<59:66>
DelayN	1001	0-500nA	8	250nA ⇒ 582mV	I	1.95nA	<85:92>
THL	0110	0-2.2V	10+4	1.16V	V	398μV	<99:112>
THH	1100	0-2.2V	10+4	1.16V	V	398μV	<113:126>
FBK	1010	0-2.2V	8	1.18V	V	9.19mV	<127:134>
GND	1101	0-2.2V	8	1.18V	V	9.19mV	<135:142>
THS	0001	0-51.8nA	8	25.9nA ⇒ 1.47V	I	202pA	<180:187>
BiasLVDS	0010	0-382 μA	8	197μA ⇒ 1.603V	I	1.54μA	<226:233>
RefLVDS	1110	0-817mV	8	417mV	V	3.19mV	<234:241>

Figure 4.3: The Medipix2 MXR DACs (Llopart, 2006)

DAC Name	DAC Code	DAC Register <LSB:MSB>	Length	DAC Range	Mid Range Value (After Reset)	DAC Step	Ext DAC Range [0 to 1 V]
Threshold[0]	00001	<46:54>	9 bits	0 to 511 nA HGM: 0 to 14819 e- LGM: 0 to 25550 e-	255 nA (1.05 V) HGM: 7395 e- LGM: 12750 e-	1 nA HGM: 29 e- LGM: 50 e-	250 nA/V HGM: 7250 e-/V LGM: 12500 e-/V
Threshold[1]	00010	<55:63>					
Threshold[2]	00011	<64:72>					
Threshold[3]	00100	<73:81>					
Threshold[4]	00101	<82:90>					
Threshold[5]	00110	<91:99>					
Threshold[6]	00111	<100:108>					
Threshold[7]	01000	<109:117>					
Preamp	01001	<118:125>	8 bits	0 to 5.1 µA	2.56 µA (355 mV)	20 nA	5 µA/V
Ikrum	01010	<126:133>	8 bits	0 to 51 nA	25.6 nA (970 mV)	200 pA	50 nA/V
Shaper	01011	<134:141>	8 bits	0 to 1.02 µA	512 nA (1.03 V)	4 nA	1 µA/V
Disc	01100	<142:149>	8 bits	0 to 2.04 µA	1.024 µA (0.84 V)	8 nA	2 µA/V
Disc_LS	01101	<150:157>	8 bits	0 to 1.02 µA	512 nA (270 mV)	4 nA	1 µA/V
ThresholdN	01110	<158:165>	8 bits	0 to 1.02 µA	512 nA (320 mV)	4 nA	1 µA/V
DAC_pixel	01111	<166:173>	8 bits	0 to 34 nA	17 nA (1.25 V)	133 pA	33 nA/V
Delay	10000	<174:181>	8 bits	0 to 204 nA	102.4 nA (1.02 V)	800 pA	200 nA/V
TP_BufferIn	10001	<182:189>	8 bits	0 to 10.2 µA	5.12 µA (1.12 V)	40 nA	10 µA/V
TP_BufferOut	10010	<190:197>	8 bits	0 to 255 µA	128 µA (1.04 V)	1 µA	240 µA/V
RPZ	10011	<198:205>	8 bits	0 to 1.5 V	640 mV	5 mV	1 V/V
GND	10100	<206:213>	8 bits	0 to 1.275 V	640 mV	5 mV	1 V/V
TP_REF	10101	<214:221>	8 bits	0 to 1.275 V	640 mV	5 mV	1 V/V
FBK	10110	<222:229>	8 bits	0 to 1.275 V	640 mV	5 mV	1 V/V
Cas	10111	<230:237>	8 bits	0 to 1.275 V	640 mV	5 mV	1 V/V
TP_REFA	11000	<238:246>	9 bits	0 to 1.275 V	640 mV	2.5 mV	1 V/V
TP_REFB	11001	<247:255>	9 bits	0 to 1.275 V	640 mV	2.5 mV	1 V/V

Figure 4.4: The Medipix3 DACs (Ballabriga et al., 2009). There are substantial changes to the DAC list, including their bit offsets, in version 3.2 of Medipix3.

A block of digital to analog convertors (DACs) supplies programmable voltages and currents to the pixel pulse analysers and to other systems in the Medipix chip. They are referred to as "global" because they affect every pixel, or, for example for LVDS, the chip as a whole.

Figure 4.3 is a table describing the Medipix2 MXR global DACs. Figure 4.4 shows the Medipix3 global DACs.

There are several kinds of DAC:

THRESHOLD DACs These DACs set the discriminator threshold to every pixel. You need to set these DACs to be able to select photons above the specified energy.

PIXEL EQUALISATION MASTER DACS These DACs set the current(s) used by the pixel equalisation DACs. These are set as part of the pixel threshold equalisation process and are matched to the final pixel DAC values. If you change one, you may have to change the other.

LEAKAGE COMPENSATION AND RESET The `Ikrum/IKrum` DAC performs two essential functions. It specifies the amount of diode leakage current to be bypassed. It also determines the rate at which the preamplifier integrating capacitor is reset so that it can properly handle a new incoming pulse.

PREAMPLIFIER INPUT AND OUTPUT LEVELS These DACs set the voltage levels of the CSA (preamplifier) input and output. The choice of voltages depends on sensor diode polarity. In Medipix3 v3.0 there are some chip performance problems, and the DACs have to be set to values established as workarounds by the Medipix developers.

BIAS CONTROL Bias DACs set bias voltage and current for various components of the pixel amplfier, shaper and discriminator. The default value, halfway between minimum and maximum, is usually recommended.

LVDS The MXR allows the LVDS communication interfaces to be tuned. Choosing an inappropriate value will break the communication link between camera and chip. The recommended values should not be altered.

MEDIPIX3 TEST PULSES The test pulse DACs in Medipix3 are used to control the amount of charge injected into the preamplifier via the test input capacitors, while the pulse time is set by an external digital input. In Medipix2 the quantity of charge at the test input is set by the voltage from an external input.

4.2.9 External interfaces

The external electrical interface appears at the row of metallic pads filling one edge of the Medipix chip. On the MXR a small number of pads turn the corners at each end of the filled edge. On Medipix3 some of the pads (power and ground) are accessible from the edge opposite to the “periphery” (the thin section of global DAC circuits along one of the four sides of the pixel matrix). Medipix3 also has through silicon vias (TSVs) which provide the electrical interface from conductive points on the underneath of the ASIC.

The signals that are carried by the interface pads are described in the following paragraphs. This list does not cover all signals supported by the two chip types. For example, the MXR has a 32-bit parallel interface that can be used to read matrix data, but which isn’t used in the MARS camera.

POWER SUPPLIES AND GROUNDS There are several independent power supply “domains” to minimise noise interference between digital circuits (such as the pulse counters) and the sensitive pixel preamplifiers. It is essential that these domains are fed from separate sources to avoid "contamination" of the analog pulse processing circuits. The MXR has three domains, all of which operate at 2.2 volts: analog, digital, and LVDS (low voltage differential signalling; see next item). The Medipix3 has four domains: analog and digital (1.5 volts), fuse-programming (3.3 volts), peripheral input/output (2.5 volts).

LVDS Low voltage differential signalling is a physical interface protocol to transfer rapidly changing digital data with minimal interference to other circuits, and good immunity to interference. It uses relatively low voltages on a pair of wires. When a digital level changes, both wires change voltage at the same moment, but in opposite directions. One wire becomes slightly more positive at the same moment that the other becomes slightly less positive (where both are approximately 1.2 volts). Because they change simultaneously in opposite directions, they don't radiate as much energy as ordinary digital lines. And because they are "differential", they are relatively immune to external interference. All interface lines in Medipix3 use LVDS, while some MXR control lines are conventional.

SERIAL COMMUNICATION There are a pair of LVDS lines for each of the following: handshake signals (`Enable_In` and `Enable_Out`); clock signals (`Clock_In` and `Clock_Out`); and data signals (`Data_In` and `Data_Out`). In the input direction, to Medipix, they carry control values to internal registers (`FSR` in the MXR, `OMR`, `DAC`, `CTPR` in Medipix3), and matrix settings to the counter matrices. In the output direction, from Medipix, they carry status information (`Fuses` in MXR and Medipix3, `OMR`, `DAC` in Medipix3) and the contents of the counter matrices.

CONTROL In the MXR these are standard CMOS level digital signals: `Reset` to reset the chip; `Shutter` to start and stop pulse counting; `M0, M1` to specify the region (FSR or matrix) that is to send or receive serial data; and `Polarity` to select positive or negative going pulses at the preamplifier input. In Medipix3 the control signals are LVDS pairs: `Reset` for chip reset; `Shutter` to control pulse counting; `MatrixFastClear` to clear the counter matrices; and `TP_Switch` to generate pulses to the test capacitors at the preamplifier inputs.

ANALOG In the MXR there are two analog inputs: `ExtDAC` to override an internal DAC; and `Test_In` to generate pulses to the test capacitors at the preamplifier inputs. The MXR has one analog output: `DAC_Out`, to allow external monitoring of one of the internal DACs. Medipix3 one analog input and one output for DAC override and monitoring: `ExtDAC` and `DAC_Out`.

4.3 Functional description

A Medipix detector is a set of 65536 pulse height analysers each of which is connected to a radiation sensing diode. The pulse height analysers are independent of each other in a Medipix2 and in a Medipix3 when it is in single pixel mode. When a Medipix3 is in charge summing mode, the analysers are organised into groups of four pixels which combine their inputs and allow just one of the four, the one with the largest instantaneous input, to be assigned the combined input. Irrespective of the mode, the discriminators are constantly exposed to the possibility of an input pulse, and will always pass a pulse through if it meets or exceeds the local threshold (which is the sum of the global threshold DAC and the pixel equalisation DAC).

The discriminator output pulses will only have an effect if the Medipix detector's `Shutter` signal is enabled. When it is enabled, or "open", each pixel counter is incremented whenever the associated discriminator passes through a high-enough input pulse (until the counter has reached its maximum, overflow value). An "exposure" is said to be taken.

If the `Shutter` signal is not enabled, the pulse height analyser circuitry continues to operate, but the counters don't count. At this time the counters may be programmed through the serial communication interface, with new values, or they may be read out. Programming the counters loads the pixel configuration registers and sets the pixel equalisation DACs. Reading the counters out has the side-effect of setting them all to zero in preparation for a new exposure.

The Medipix detector has auxiliary circuitry, the global DACs, to set the operating voltages and currents of the pulse height analysers. Most of the time, the only circuit that is likely to be altered frequently is the global threshold DAC for each discriminator. This DAC determines the minimum level for an input pulse to be counted, and therefore selects charge pulses based on the photon energy that created them. Any pulse from a photon with a certain minimum energy will be counted, and a picture of the energy distribution of an ongling stream of photons, such as from an `x`-ray tube, can be obtained by "scanning" through a range of global threshold DAC values. For each threshold value an exposure is taken by opening and closing the `Shutter` and reading the counters. From the accumulated set of counts, the energy distribution of the photon stream at each pixel is obtained simply taking differences between the successive exposures.

The global DACs are programmed by a similar method as that used to load the pixel configuration registers, through the serial communication interface. There is a DAC register for each DAC that stores a (binary) number. The DAC circuit generates voltage or current in proportion to the stored number, and this generated analog level is distributed to the detector pixels.

Medipix3 has a number of optional settings that can be programmed into the operation mode register (OMR). For example, single pixel mode, or charge summing, is specified by a single binary bit in the OMR.

The remainder of this section provides more details about the Medipix functions introduced here.

4.3.1 Medipix reset

The Medipix chip is reset by a pulse from the `Reset` control signal. Afterwards each Medipix DAC is automatically set to the middle of its numerical range. It is usual for the DACs to be reloaded, since for a number of them the mid-range value is not appropriate. A reset does not alter the pixel configuration registers, but it is recommended that they be loaded with known values.

4.3.2 Clearing the counters

It is also essential that the counters be set to zero before taking an exposure. This is done automatically each time that the counter matrix is read out. For example, they will be automatically cleared by reading back the matrix after loading the pixel configuration registers.

The Medipix3 control signal `MatrixFastClear` can be used to clear the counters without the need for a complete readout of the matrix.

4.3.3 Shutter

The `Shutter` control signal determines which of two states the Medipix chip is in. When the `Shutter` signal is active, the shutter is open and each pixel is an independent pulse analyser that runs continuously and asynchronously. Its front end amplifier, shaper and discriminator process incoming charge pulses from the preamplifier input. The counter is triggered if the input charge pulse exceeds the discriminator threshold. However, once the counter has reached its overflow value, further triggers have no effect.

When the shutter is closed due to `Shutter` being inactive, the counter matrix is reconfigured into a set of shift registers that can be read out or written. The front end circuits do however continue to operate, but no counting takes place.

4.3.4 Serial communication

The Medipix chip uses serial digital communication to receive commands that load the registers, and to receive data to be stored in the pixel configurations registers. In the same way it transmits information in response to a command, and to send the matrix of counter data. Serial communication uses three kinds of signals: handshake lines, clock lines, and data lines. Medipix depends on an external "master" to initiate, synchronise, and complete the various possible communication transactions.

HANDSHAKE LINES The master begins serial communication by changing the state of the input handshake line. There is an input and an output handshake line: `Enable_In` and `Enable_Out`. The `Enable_In` line, from the master, is made active to begin communication. The `Enable_Out` line is made active by Medipix to respond to the master request for communication. It is set inactive by Medipix when, according to its internal counter, it has completed its response to a communication transaction.

CLOCK LINES Serial communication is the transfer of bits of data in sequence, coordinated by an oscillating "clock" line. The `Clock_In` signal is controlled by the master, while `Clock_Out` is controlled by Medipix. The source of the data (master or Medipix) first sets the data bit (to 0 or 1), then the clock line changes state. The receiver of the data relies on the change in clock line to indicate that a data bit is ready, and reads the data line to get the value of that bit. Medipix reads a data bit when the clock line changes from 0 to 1, and it makes its data available so that the master can read it when the clock goes from 1 to 0. When the master requires data from Medipix, it simply sends a series of clock signals and accepts the data, bit by bit, from Medipix after each clock cycle. Medipix is "aware" of how many bits of data it has available, and changes the state of its `Enable_Out` line when it has no more data to send.

DATA LINES Both Medipix2 and Medipix3 receive data on a single line, `Data_In`. There are two options for data output: the single `Data_Out` line, or a multiple line data bus. Medipix2 has a 32-bit data bus, while Medipix3 has an 8-bit bus that can be used in 1-bit, 2-bit, 4-bit or 8-bit mode. The MARS camera firmware currently supports only single bit readout for both types of Medipix chip, even though some Medipix3 chip carriers have connections to some or all of the data bits.

4.3.5 Communication transactions

There are two kinds of transaction that can be performed when communicating with a Medipix chip: register write and read, and pixel matrix write and read. The method by which a transaction is specified differs between Medipix2 and Medipix3. Medipix2 has two control signals, `M0` and `M1`, that determine the kind of transaction to be performed. Medipix3 relies on a 4-bit command pattern at the front of a stream of serial bits. There are two 4-bit commands: one, to load the operation mode register (OMR). The OMR includes three "mode" bits that specify an operation to be performed. The second 4-bit command triggers the operation that has been specified in the OMR mode bits. The mode bits select which register will be read or written, or which of the counter matrices is to be read or written.

REGISTER WRITE AND READ Medipix2 has only one register that can be written: the Fast Shift Register (FSR). This register can not be read out; instead, the fusible chip identification register is transmitted each time the FSR is written.

Medipix3 has three registers that can be written, and two that can be read. The writeable registers are the OMR, the DAC register and the test pulse register (CTPR). The two that can be read are the OMR and the DAC register. At the same time that the OMR is read, the Medipix3 fuses are also sent.

PIXEL MATRIX WRITE AND READ "Pixel matrix" is a common term referring to the one or two sets of 65536 pixel configuration registers when they are written, and counters when they are read. Medipix2 has one matrix, Medipix3 has two. The matrix is usually written just once in order to load the pixel configuration registers. It is necessary to read it back immediately after loading in order to zero the pixel counters.

Writing a numerical pattern to the matrix, reading it back, and comparing the result with the original pattern, is an effective test of the matrix memory. Failure of a transistor in one of the shift registers is sometimes seen; the usual symptom is that an entire column of 256 pixels fails this memory test. Some failures are pattern sensitive; this is a known problem in Medipix3.

It is not necessary to write the matrix with zeros after reading the counters, since they are automatically set to zero by the reading process.

4.3.6 Medipix registers

MEDIPIX2 FSR The fast shift register, FSR, combines several functions. Firstly, it is used to load the Medipix2 DAC registers. Secondly, it can be used to select a DAC to be monitored via the `DAC_Out` line, and to select a DAC to be overridden via the `ExtDAC` intput. Finally, it allows the Test Pulse register to be loaded.

MEDIPIX3 OMR The operation mode register, OMR, handles three command mode bits referred to earlier. The OMR also allows a number of Medipix3 options to be specified. Not all of these options are listed here, since the MARS camera firmware does not support all the available Medipix3 features. Options that can be set are pulse polarity, charge summing mode, counter depth (12-bit or 24-bit), spectroscopic mode (also known as colour mode), the DAC to be sensed via `DAC_Out`, or a DAC to be overridden via `ExtDAC`. Generation of Test Pulses is enabled and disabled in the OMR.

A number of options have been omitted because they alter Medipix3 behaviour and make it incompatible with inflexible low level functions, both in the camera and in the PC library. For example, changing the counter sizes reduces the number of bits that are sent during matrix reading. The same thing happens if the "Region of interest" or ROI functions are used. The data bus width setting can not be changed since multiple bit transfers are limited both by firmware and by motherboard hardware. Future firmware (and hardware) releases may allow these options to be supported.

MEDIPIX3 DAC REGISTER The register is written whenever a DAC is to be programmed. The register can be read back, and this may be useful in case the current values are not known by the remote control PC. For example, after a reset the registers should take on their default values, and reading them can be used as a check for prior operation of the reset function.

TEST PULSE REGISTER Test pulse support has been included in the MARS camera firmware, but has not been successfully tested. Both Medipix2 and Medipix3 allow test pulses to be generated in a selected set of pixel columns. These colunns are selected by a register in which each bit corresponds to one of the 256 columns. The pixel configuration register is used to individually enable or disable test pulses, pixel by pixel.

FUSES Both Medipix2 and Medipix3 have a set of programmable "fuse" bits that label the chip with a unique number. These fuses are usually set at the time of Medipix testing on a wafer, and are not alterable. They are useful as a way of uniquely identifying a Medipix chip. The Medipix2 fuses are transmitted to the master during the FSR write process. Medipix3 reports its fuses during the OMR read process.

MEDIPIX3 V3.0 ISSUES The first version of Medipix3, v3.0, has some design and manufacturing flaws. Some require software workarounds; others prevent features being used.

There is a problem with `Cas`, an important bias DAC to the Cascode circuit, part of the preamplifier. The DAC output conflicts with another signal and can not supply the necessary current to the Cascode. The DAC has to be overridden using the `ExtDAC` input. This workaround is performed in the PC software.

Two other DACs, `GND` and `FBK`, are highly sensitive to the Medipix ASIC temperature. The MARS camera Peltier cooler provides some protection against this problem.

There are problems in serial communication that cause loss of data from pixel counters, and that disrupt the process of loading or clearing the pixel matrix. Workarounds, that add some overhead to the communication process, have been found and are performed in the camera firmware.

The Medipix3 "Continuous Read and Write" function, which allows one counter to be operating while the other is being read, is not usable.

The Medipix3 "Full sequential" mode is available but requires a special sequence of commands, which includes use of the `MatrixFastClear` signal.

4.4 Pragmatics

4.4.1 Sensor materials

SILICON Silicon, which has atomic number 14, is available in high purity and at low cost and is a commonly used sensor material with Medipix2 and Medipix3 chips. The thickness is usually 300 μm. Single and quad (a cluster of Medipix chips in a 2×2 array) size crystals are used. The preferred charge carriers are "holes", which requires that the common electrode is positive with respect to ground. Silicon gives good imaging performance with a bias voltage of 100 volts. The stopping power reduces quickly for photons above 25 to 35 keV, although members of the MARS team obtain information usable in discriminating some kinds of material in energy bins that reach up to 50 keV.

CADMIUM TELLURIDE (CDTE) CdTe has atomic numbers 48 (Cd) and 52 (Te), and has much greater stopping power than silicon for x-ray photons. The thickness of the CdTe sensors we have worked with has been 1 mm. Bulk CdTe is slightly p-type, and the mobility of electrons is considerably higher than for holes. For best performance CdTe chips are set to count electrons, and the common electrode is connected to the negative side of the high voltage bias supply. Bias voltages of up to 450 volts are commonly used. Photons of up to 120 keV can be detected due to the high stopping power of CdTe.

The production of CdTe crystals is not as easy to control as that of silicon. Dislocations are common, seen as curved lines ("wrinkle patterns") in flat field images. Small spot defects, suspected to be associated with local high concentrations of tellurium, appear as black spots. These imperfections are partially removed by "flat field correction".

Bump bonds with CdTe are seen to be less reliable than with silicon and areas of partial failure, zones of unresponsive pixels, are seen on chips that the MARS team has used.

GALLIUM ARSENIDE (GAAS) GaAs, with atomic numbers 31 and 33, is intermediate in stopping power between silicon and CdTe. Depending on doping, positive or negative bias voltage, around 300 volts, is used. GaAs was the first material to be bonded to the Medipix1 chip, and GaAs sensors produced in Tomsk and JINR, Dubna are currently being re-assessed by the MARS team.

4.4.2 Counter matrix bit sequence

The matrix of pixel counters in Medipix appears logically as an array of 2^{16} memory registers. They can be are written by transmitting a stream of binary (bit) data to the chip. This is required when loading the pixel configuration registers. Immediately after being written they can be read out for checking. After an exposure has been taken, by opening and closing the shutter, the pixel memory registers contain the pulse counts. Medipix2 has a single 14-bit counter per pixel, and Medipix3 has two (of variable size: 1-bit, 4-bit, or 12-bit).

The sequence in which bits are written and read is determined by the columnar organisation of Medipix chips. There are 256 columns, and bits are accessed a column at a time. For Medipix2, the first 256 bits written become the "high order bit" of the 256 pixels in the very bottom row of the chip. The next 256 bits are the second highest bit of the bottom row, and so on until 14 sets of 256 bits have been sent. The next 14 sets of 256 bits are stored in the second from bottom row of pixels, and so on until the top row of pixels has been loaded.

When the pixel matrix is read out, the first bit to be read is the high order bit from the pixel in the bottom row and rightmost column, followed by the high order bits of the neighbouring pixels in the same row. After 14 sets of 256 columns are read, the second last row is read out, and so on. For Medipix3 a similar process occurs, but has to be done twice since there are two sets of register/counters.

The order of bits written and read can be seen to be "scrambled". The terms "serialisation" and "deserialisation" refer to the process of converting a matrix of numbers into the Medipix bit order prior to loading them into the chip, and back again after readout. In the MARS camera these operations are performed in the MARS PC library.

4.4.3 Chip function tests

The first of the following sections describes an automatic technique to detect the presence of Medipix chips in a chip carrier that can be tiled with more than one arrangement of chips. It is performed each time the PC accesses a MARS camera. The later sections describe techniques which are available to check that the Medipix chips in a new camera are working correctly, or to investigate problems with a camera.

AUTOMATIC CHIP DETECTION Some Medipix chip carriers (see section 5.3) have space for more than one chip to be mounted, but do not have a chip fitted in every possible location. To avoid the need to specify the chip configuration, there are techniques by which Medipix chips can be detected automatically. The MARS chip carriers for Medipix2 and Medipix3 are both assembled with variable tilings.

The technique used with Medipix2 is to test the state of the chip's output clock line, `Clock_Out`. On Medipix2, the output line is the logical inverse of the input. When the clock input is at the low (inactive) level, the output is high (active), and vice versa. For each Medipix2 chip position the camera software can set the clock lines to their two values and check that the output is the opposite of the input. This check is performed by the camera firmware, which creates a table showing whether or not there is a chip present at each of the (six) physical locations on a chip carrier. This list is accessed by the PC software, after connecting to the camera, to determine how many chips should have memory allocated for image storage.

With Medipix3 an attempt is made to read a register from the chip and the result checked for a normal response. If a chip is present, its output enable line, `Enable_Out`, changes state after the correct number of clock pulses have been received. The camera checks for this and returns an error response in its absence. The MARS PC software coordinates the process by sending an OMR read request to each of the possible chip positions. If the request leads to a normal response from the addressed chip, memory is allocated for it.

DAC SCANNING In both Medipix2 and Medipix3 the DACs are set by writing their values to a register on the chip. DAC scanning is the process of setting up a DAC to be looped back to the analog output line, of setting that DAC to a range of values, and of observing the response of its output. This is a straightforward test of communication and of chip function. Even if done with only a single DAC, the observation that the DAC output changes with its programmed setting is a strong demonstration that communication with the chip is working, and that the chip power supplies are correct.

If the chip's analog power supply is not correct, a DAC scan can appear to succeed because communicating and DAC programming rely on the digital supply. The output voltage from the DAC, as measured by the camera's ADC, provides evidence of the incorrect analog power supply.

MATRIX WRITE VERIFICATION When the pixel matrix has been written with a known pattern, it can be read back to check that the registers have been programmed and have stored the intended values. Since some kinds of error are pattern sensitive, a variety of values may be used to perform comprehensive testing.

SHIFT REGISTER COLUMN FAULTS Since the pixel matrix is organised into columns, a faulty transistor in a shift register will make all of the pixels in a column inaccessible. This fault is revealed by a matrix write verification test. A significant number of Medipix3 chips, perhaps as many as one in ten, have been seen with one or more columns of inaccessible pixels.

Medipix chips are graded using test equipment at CERN. The Medipix2 MXR manual defines a classification scheme for chips according to the number of errors. A representative statement is: "The classification of the good chips is as follows: A: All pixels digitally working, <10 missing pixels in the analog test and good DACs. B: Up to 1 dead column in the digital and analog test and good DACs. C: Up to 2 dead columns in the digital and analog test and good DACs." (Llopart, 2006). The Medipix3 manual does not define a scheme, possibly because the yield of usable chips was very poor for version 3.0. Fortunately, the newer versions are reported to be much improved in their manufacturability.

FRONT-END NOISE SCAN The preamplifier or CSA of each pixel pulse processing circuit is exposed to electrical noise from the sensor and from the circuit components. The noise acts like a weak signal, lower in level than the pulse from a detectable photon charge cloud. Noise can be used as a test signal for the amplifier by choosing a suitably low setting for the threshold DAC (`THL` in Medipix2, `Threshold0..1` in Medipix3). The noise generates pulses at high rates, hundreds of thousands or millions per second in each pixel. The threshold at which noise is seen at the discriminator varies between pixels. This is due to manufacturing variations that cause random deviations in the DC offset from the front end amplifiers, as well as in the threshold detector. A scan across all threshold DAC values is usually done to find the extremes at which noise pulses start, them stop, in each pixel. Some pixels do not produce counts at any threshold DAC value This almost certainly means that the pixel circuitry is faulty, and the pixel should excluded from image making. At the other extreme are pixels which generate counts at all threshold settings; they should also be excluded.

RADIATION SOURCES FOR TESTING Testing the complete Medipix chip function, from sensor to counter, to shutter and to matrix readout, requires a signal from its sensor layer. That depends on the presence of the high voltage bias, and on a source of ionising radiation. In case an x-ray tube is not available (for example, outside a MARS scanner), a useful source of radiation is the small spot of radioactive material found in some kinds of smoke detector. This is commonly an americium 241 source with an activity of 1 μcurie, or 37 kBq. During its decay process, americium 241 emits alpha particles with energy around 5 MeV, and gamma photons in observable numbers from 60 keV down to around 12 keV. The alpha particles generate a large charge pulse across a cluster of pixels. They do not pass through more than around 5 cm of air and are stopped by a sheet of paper.

An x-ray tube is the definitive source of radiation for testing a Medipix chip. X-rays from a microfocus tube with a voltage of 50 kV and current of 100 μA are readily detected by a Medipix chip. A typical operating setup, with a silicon sensor at the maximum distance of around 20 cm from the x-ray tube and an exposure time of around 100 ms, can show hundreds or thousands of counts per pixel according to the threshold setting. A small metallic object interrupting the beam will create an image of recognisable contrast even without an equalisation mask having been loaded into the pixel configuration register.

BUMP BOND FAILURE A flat x-ray field (with no object between the x-ray source and the camera) will reveal pixels that are partly or completely unresponsive to radiation even though their front end circuits are working (as seen in a noise scan). This problem has been seen with GaAs and CdTe sensors, but not usually with silicon. Progressive failure of bump bonds is documented with CdTe chips and is the likely cause of areas of unresponsive pixels.

SENSOR MATERIAL DEFECTS Interlinked curved lines, referred to in our group as “wrinkle patterns”, are seen in CdTe sensors fitted to Medipix2 and Medipix3. CdTe sensors also show dark spots, groups of pixels that may be surrounded by a bright halo. These flaws are only partially mitigated by flat field correction. There is some controversy about the cause, though “subgrain boundaries” seem to be an obvious suspect.

4.4.4 Medipix2 LFSR counters

The Medipix2 pulse counter is a 14-bit linear feedback shift register, and has a gamut that is less than the full range for a 14-bit counter of 0 to 2^{14}-1 (16383). There are 11810 valid non-zero patterns. The MARS PC library automatically translates these patterns into counts. When there is a very high pulse rate, such as when the front end circuit noise triggers the threshold crossing detector, the LFSR is known to generate invalid patterns. These are indicated by the PC software with a distinct value. When a pixel counter has this value it is not a real count and should be ignored. These invalid patterns are occasionally seen during normal x-ray image taking.

4.4.5 Advice on DAC settings

Medipix2 has thirteen DACs. All but two have a resolution of 8 bits; the two threshold DACs (`THH` and `THL`) are made of two ganged DACs, each of which has a combined resolution of 14 bits. Medipix3 has twenty five DACs. Fifteen have a resolution of 8 bits. The threshold DACs (`Threshold0...Threshold7`) and the test pulse DACs (`TP_REFA/B`) have a resolution of 9 bits.

The choice of value for the threshold DACs in both chip types is determined by the required energy threshold. The mapping of energy to DAC value is found by energy calibration.

The number of possible values of the Medipix DACs creates a huge number of possible internal states: 2^{88+28} for Medipix2, 2^{120+90} for Medipix3. Fortunately, the Medipix chip designers prescribe standard values for most of them, although there are some gray areas. The standard DAC value, when not otherwise advised, is the mid-range value: 128 for an 8-bit DAC, 256 for a 9-bit DAC.

LEAKAGE COMPENSATION DAC This DAC, with the name `IKrum` and `Ikrum` in Medipix2 and Medipix3 respectively, is an abbreviation from I (for current) and "F. Krummenacher". He is the inventor of the compact front-end design, used in Medipix and other detectors, for pixel front-end amplifiers using CMOS transistors. The DAC has two effects: it provides a DC correction for leakage current from the pixel sensor diode, and it performs the restoration of DC level from the charge sensitive amplifier (preamplifier) feedback capacitor. The Medipix chip designers recommend that the DAC be set to 20 in both chip versions. Note that due to the second stated effect on DC restoration, altering this DAC will affect the maximum count rate in Medipix2 and Medipix3.

GROUND AND FEEDBACK DACS `GND` sets the voltage level of the pixel electrode. When holes are to be counted, the desired level should be close to 0 volts. When electrons are counted, the desired level is greater than 0, because an electron pulse causes a negative-going pulse from the pixel electrode.

`FBK` sets the voltage level of the preamplifier output. The preamplifier inverts the direction of an input pulse so the choice of value for this DAC is determined by the pulse polarity. Electron counting, with negative input pulses and positive output pulses, requires that the output level be close to 0. Hole counting, which leads to negative pulses from the preamplifier, requires that the quiescent output level be positive.

In Medipix3 the recommended values for these DACs are tied to those for the special handling of the `Cas` DAC, mentioned below in section 4.4.7.

MASTER EQUALISATION DACS There is a single DAC in Medipix2, `THS`, and two DACs in Medipix3, `DAC_pixel` and `ThresholdN`, that control the behaviour of the pixel threshold equalisation DACs. The choice of settings for these master DACs is made during the process of pixel equalisation, and depends on the distribution of offset errors in the pixels of each individual Medipix chip. See section 4.4.6.

OTHER DACS In Medipix2 the LVDS interface amplifiers are controlled by DACs `BiasLVDS` and `RefLVDS`. The value 240 is recommended for both. A wrong choice of value risks the breaking of communication between the camera and the Medipix chip, because it alters and can disrupt the physical levels of the clock and data signals.

4.4.6 Pixel threshold equalisation

Medipix2 provides a 3-bit DAC for each pixel, for each of the two threshold crossing detectors. Medipix3 provides a 4-bit DAC for pixel for each of the two threshold crossing detectors.

4.4.7 Design faults and workarounds

MXR MODE LINE INTERACTIONS On a chip carrier with two Medipix2 MXR chips fitted, an extra toggle of the mode lines (M0 and M1) is necessary on a chip after it had been accessed. The symptom is banding that can be seen in an image of the counters retrieved from the chip. The chips share mode lines and this is presumed to be the cause of the problem, which has not been seen on single chip carriers.

MEDIPIX3 `CAS` DAC This DAC was found to be ineffective, due to a design problem, in early testing at CERN. The external DAC input is used to override the weak on-chip source. Advice on the appropriate settings of the DAC, as well as for the related DACs `GND` and `FBK`, is provided in the Medipix3 manual (Ballabriga et al., 2009, ch 9).

In addition, `CAS` and `FBK` are very sensitive to chip temperature. Peltier cooling of the chips is a solution to this problem.

MEDIPIX3 CSM THRESHOLD DISPERSION Charge summing mode (CSM) has significant distortion in the allocation of summed charge pulses. Two of the pixels, in even rows and columns in each group of four, receive a greater than expected share of the aggregated charge pulses. This problem can be seen when using a source known to generate multi-pixel charge clouds, such as an alpha article source. Chapter 9 reports some measurements that demonstrate this effect.

MEDIPIX3 SHIFT REGISTER CORRUPTION In some chips, many 1 bits are altered to 0 during shifting of data out of the counter matrix. Counter C0 is the more severely affected. In some chips the problem is worst when alternating 1s and 0s are transferred; this is referred to as "high frequency" data. In other cases the problem is related to bit position within the three groups of four bits in the 12-bit counter.

Chips with these problems will be identified using the matrix write verification test described in section 4.3.5.

MEDIPIX3 RANDOM TELEGRAPH SIGNALLING (RTS) Random shifts in DAC output, seen as a "dithering" in value (switching between two values, like morse signalling on a telegraph line) during a series of exposures at constant value of `Threshold0`, have been observed during series lasting an hour or less. This is suspected by CERN to be caused by random telegraph signalling or RTS, a known phenomenon in IC designs with thin oxide layers (Kogan, 1996; Grasser, 2012).

MEDIPIX3 SHIFT COUNTER RESET Special additional clock sequences, and specific ordering of counter accesses, are necessary to ensure correct readback of counter matrices. It is not possible to use the Continuous Read/Write option due to this fault. The problem remains in version 3.1, but has been eliminated in the redesigned version 3.2 of Medipix3.

4.4.8 Power supply issues

During the early development of MARS camera with a Medipix2 chip, digital and analog power supplies were joined by connecting both to a single supply. This caused mystifying problems in achieving the full range output from the threshold DAC `THL`.

On Medipix3, the power supply lines to the Hex six-chip carrier have been seen to become noisy, with an oscillation of arond 5 kHz. Their voltage, measured close to the chip, can droop in value by 100 mV or more when some of the chips are "in the noise" during a threshold scan. There appears to be a significant increase in the current drawn when many pixels are subjected to high count rates. This may also happen during exposure of the sensor to a high flux of photons. The shift in power supply voltage will cause changes in threshold levels and has the potential to alter the relationship of key internal signals, such as the thresholds. Medipix3 includes a second set of power supply pads, and the CERN chip carrier has voltage controllers close to the Medipix chip; use of one or other of these protective measures may be needed in the MARS chip carriers.

4.4.9 Radiation effects

ASIC DAMAGE Long term exposure to radiation is known to cause both reversible and irreversible changes in the semiconducting materials of Medipix sensor and ASIC. Medipix3 uses best practice to protect vulnerable transistors, the Enclosed Layout Transistor. One observable effect of long term irradiation is a systematic change in the pattern of equalisation DAC values in pixels that receive high doses. CERN, a place at which high radiation doses are a normal part of the life for semiconductor detectors, uses an annealing process that can reverse some of the effects, those due to absorbed O_2 on a surface. Many published papers in detector physics, for example Li et al. (2006), refer to this use of annealing.

FLUORESCENCE FROM BUMP BONDS Metals used in variations of the flip-chip bump bonding process include silver, indium, lead and tin. When the spectrum of incident x-rays contains photons of an energy that causes characteristic radiation in the bump bonds, these fluorescence photons may be observed as an extraneous signal in the image. It has been pointed out (Butler, 2012) that the problem is overstated: low Z sensor materials like silicon are ineffectual at imaging photons energetic enough to evoke fluorescence in heavy metals, while high Z materials like cadmium telluride will almost certainly stop such photons before they reach the metal bumps.

Chapter 5

Electronics and hardware

Contents

The MARS camera electronics and hardware system was introduced in chapter 3. In this chapter a comprehensive view is given of the standard and optional components of a MARS camera. The standard components are the motherboard, high voltage board, cooling system and the camera case. There are several chip carrier options.

The motherboard and high voltage board were designed and manufactured by ILR Ltd, by, or under the supervision of, Marcus Clyne. The multi-chip MARS chip carriers were designed by ILR but were manufactured and assembled overseas. The most recent versions were manufactured in Switzerland to exacting specifications.

My purpose in writing this chapter is to describe the operating environment for the camera firmware. I have from time to time had to track down problems in the hardware: manufacturing faults, or simple omissions in interface functions in the firmware. Consequently I have became quite familiar with the electronic circuit designs, and I think it is worthwhile to record the essentials of what I know. The authoritative references from which I obtained this knowledge are the circuit schematics, as well as the manufacturer specifications for devices such as the Altera Field Programmable Gate Array (FPGA) and the National Semiconductor DP83865 (the Gigabit Ethernet physical interface).

Some duplication of details from chapter 3 is seen here. That is because my intention in that chapter was to explain choices made in the hardware design. Also, chapter 6 refers to some of the hardware subsystems described here. There is a close match between the hardware circuits (including FPGA logical units) and the low level firmware functions, described in chapter 6, through which the hardware is accessed.

5.1 Motherboard

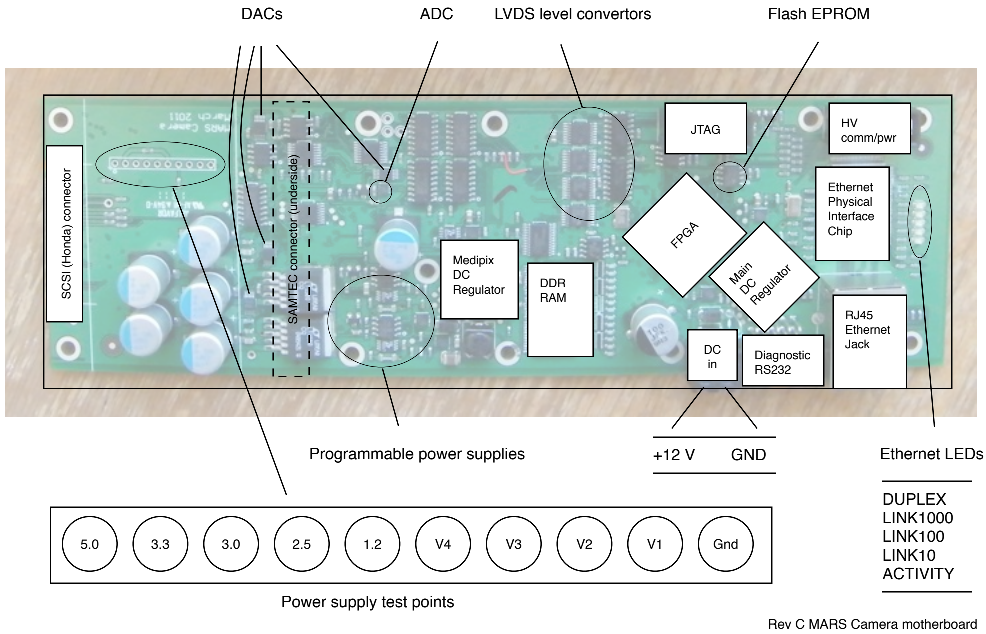

Figure 5.1: Photograph of a MARS camera motherboard. The connectors and large integrated circuits are overdrawn with labelled boxes. Some of the significant smaller chips and other areas of interest are also identified.

5.1.1 Overview

The motherboard, a multilayer printed circuit board, provides most of the electrical and electronic connections for one to six Medipix chips. A photo with many of the main components labelled is shown in figure 5.1. MARS chip carriers have a plug that fits into the Samtec socket on the lower surface of the motherboard. Chip carriers from CERN have a SCSI socket that connects through a cable to a transition board. The transition board has a Samtec connector to fit into the motherboard, and a SCSI (also known as VHDCI) connector for the cable from the chip carrier. Several Medipix chip carrier designs work with the motherboard and are described in section 5.3.

Medipix chips require several independent power supplies. They have a few control inputs, a number of communication signals, and some analog input and output lines. The semiconductor sensor layer needs a bias voltage, and a cooling system gives stable performance at a safe operating temperature. The HV (high voltage) board provides the bias supply and power to the cooling system, and is described in section 5.2.

Most of the digital signals to Medipix2, and all to Medipix3, use low voltage differential signalling (LVDS). It has the advantage of low power consumption at high speed, and generates relatively little electrical noise. It is also resistant to interference from other circuits and signals.

There are several power supplies for the Medipix chips. Medipix2 needs three supplies, Medipix2 needs four. Some variants of chip carrier include voltage regulators: the Medipix2 boards from CERN and Panalytical, and the Medipix3 CERN board. These boards require a higher voltage from the motherboard and step it down to the appropriate values.

As well as power for the Medipix chip carriers, there are several power supplies for the motherboard subsystems, at voltages of 5 V, 3.3 V, 2.5 V and 1.2 V.

Both chip families require control signals: such as `Reset` and `Shutter`. In addition, Medipix2 has the `Polarity` and `Mode` inputs, while Medipix3 has a `MatrixFastClear` input.

The Medipix chips use synchronous serial communication: digital signalling by which data is transferred one bit at a time, the time marked by a clock pulse.

`Enable` input and output signals accompany the clocked data, and indicate the end of a transaction.

Analog signals supply an external DAC input, `ExtDAC`, to each Medipix chip, and a DAC output, `Dac_Out` signal from each chip. Medipix2 has two additional analog inputs that are used to generate test pulses; this option has not been tested in the current camera firmware.

There are three connector types between the motherboard and Medipix chip carrier. There are two versions of SCSI, for Medipix2 (CERN and Panalytical) and Medipix3. The Samtec connector is used by the MARS multi-chip carrier boards.

A peculiarity of the Medipix3 SCSI connector is that it includes the high voltage bias supply to the sensor layer, whereas the Medipix2 relies on a separate cable. This chip carrier is used only with silicon Medipxi3 chips that operate at no more than 100 V and is believed to be safe, even if the rated voltage is 50 V. The multi-chip carriers have separate high voltage cables.

5.1.2 Motherboard subsystems

The overview of this section talked about the various signals that are exchanged between motherboard and Medipix chip(s). These signals are created and processed by a variety of digital and analog circuits on the motherboard.

In the paragraphs below, we refer to the SPI bus. SPI, Serial Peripheral Interconnect, is a simple synchronous inter-chip signalling protocol widely used to transfer commands and data between integrated circuits, especially ones with complex internal functions.

Medipix power supplies include three with programmable voltage, and one fixed 3.3 volt supply. The programmable supplies contain feedback signals. The power supply output voltages are controlled by SPI potentiometers. There are four SPI potentiometers: one for the main DC regulator, three for the supplies downstream from the regulator.

On Medipix3, all digital signals are converted to and from LVDS voltage levels by convertors. Each LVDS signal uses a pair of parallel wires that have their voltage level shifted in opposite directions according to their polarity, positive or negative.

Analog signals, `DAC_Out`, from the Medipix chips, are converted to digital values by a single analog to digital convertor (ADC). The ADC is supplied by a cascaded analog multiplexor that selects one source from the numerous analog signal sources on the motherboard. These include the Medipix chips, and the voltage and current feedback signals from the programmable power supplies. The ADC and the multiplexors are controlled and accessed using the serial SPI protocol. The multiplexors are programmed with the address of a source cignal by SPI parallel output chips.

The analog signal `ExtDAC` to the Medipix chips is generated by digital to analog convertor (DAC) chips. Each DAC chip can generate four analog outputs. The DAC chips are controlled using the SPI bus.

Some of the digital control signals to Medipix are generated by the same SPI parallel output chips that control the ADC multiplexor.

Most digital signals to and from Medipix are generated and received directly by the FPGA that is the central control system of the motherboard.

There are three other subsystems to be mentioned. The first is the Ethernet physical interface, a complex chip that can run at 10, 100 or 1000 megabits per second. It is a DP83865 “PHYTER” chip from National Semiconductor. This device performs the encoding and decoding of data into voltages at the precise clock speeds required by Ethernet. It is a very flexible device which can automatically detect the speed of the interface at the other end of the network, and is able to adapt to either of the possible wiring polarities for each of the four pairs of wires in the network cable.

The two other subsystems are the asynchronous serial interfaces that provide RS232 signalling to the high voltage board and to an external diagnostic PC.

5.1.3 FPGA, Flash EPROM, and DDR RAM

The EP3C25F324 FPGA, a device manufactured by Altera, is programmed automatically with firmware loaded off the flash EPROM (erasable programmable read only memory). It has a 50 MHz crystal oscillator to clock its internal operation; this clock is the source of the clock used for Medipix communication.

The FPGA firmware transforms this large and complex integrated circuit into several highly functional logic circuits. These are described in the remainder of this subsection.

There is a 32-bit microcontroller known as the Nios2; a DDR RAM controller for the 32-megabyte RAM chip; a Gigabit Ethernet media access controller (MAC); an array of synchronous interfaces for communication with the Medipix chips, including clock generator and counters; SPI and RS232 interfaces; and some other digital interfaces.

After the Nios2 has been installed into the FPGA during its power-on procedure, and after the RAM controller has successfuly initialised, the processor is automatically "booted" and has its firmware copied to RAM from the same flash EPROM that provided the FPGA firmware. The Nios2, running this program, coordinates all operations on the motherboard, communicating with Medipix chips, high voltage board, diagnostic PC and the MARS PC via Gigabit Ethernet.

The Medipix clock generator produces a programmable number of pulses at 50 MHz. This signal is replicated by a specialised LVDS clock chip to all the Medipix devices on a chip carrier.

For each Medipix chip there is a 32-bit shift register from which data is transmitted to the chip in synchrony with the Medipix clock.

For each Medipix chip there is a counting circuit that keeps track of the clock pulses returned by the Medipix chip.

For each Medipix chip there is a 32-bit shift register into which data from that chip is shifted in synchrony with the clock returned from that chip.

There is a single circuit that generates a timed pulse to all the Medipix shutter control lines.

There is another circuit that generates test pulses to the Medipix test pulse input lines.

A standard Altera RS232 logic module handles data communication with the high voltage board and diagnostic PC.

Various single line digital signals, such as `Enable_Out` and `Enable_In` are generated or received by standard Altera parallel input/output logic modules.

SPI communication to the external family of attached devices is performed using software “bit bashing” through a parallel input/output logic module.

Note that some digital signals are passed indirectly over the SPI bus to external devices, such as the SPI parallel outputs to select the ADC multiplexor channel. Some Medipix signals are also generated by the SPI chips.

The Ethernet Media Access Controller (MAC) is implemented in FPGA logic by a commercially licensed module from IFI in Germany. The MAC includes direct memory access (DMA) for high speed transfer of data between the CPU and the Ethernet transmit buffer.

5.2 HV board

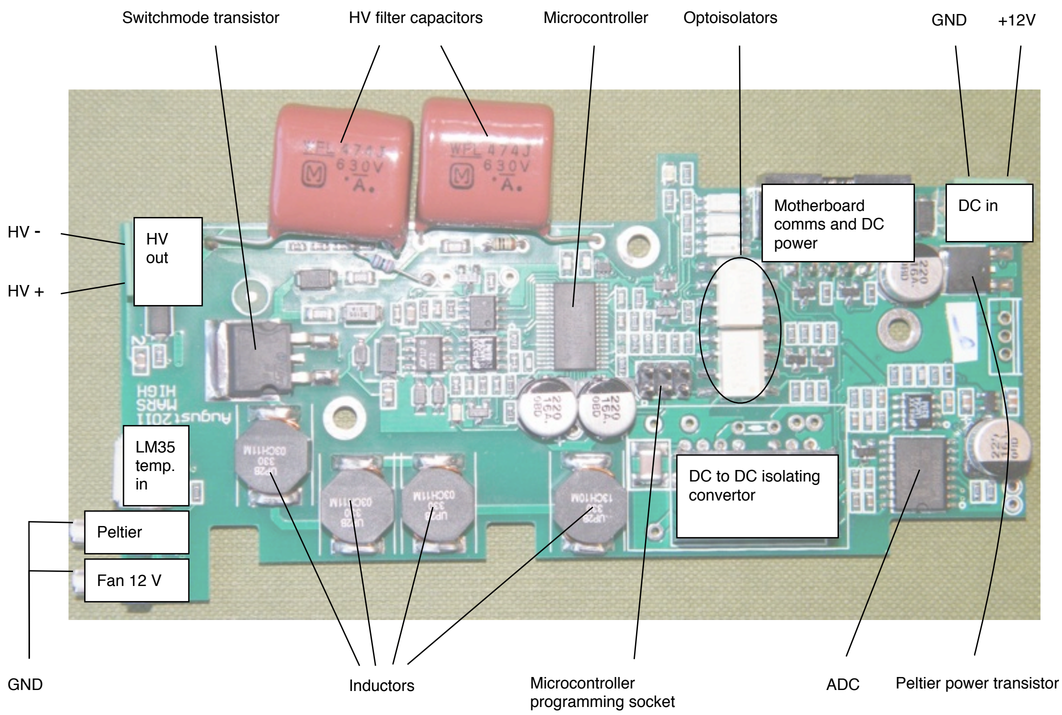

Figure 5.2: Photograph of a MARS camera high voltage board. The connectors and DC to DC isolating convertor are overdrawn with labelled boxes. The filter capacitors and other components are also identified.

The high voltage board, pictured in figure 5.2, performs two functions. It produces an isolated bias voltage for the Medipix semiconductor sensor layer. It can produce a programmable voltage in either polarity in the range of 90-500 volts at up to around 2 mA. It is stable enough to be able to supply the inrush current to multiple Medipix chips when first switched on. Its other function is to supply power to the cooling system fan, Peltier device and LM35 temperature sensor, and to read the output of the temperature sensor.

5.2.1 High voltage generator

The HV generator is isolated so that either polarity of the output can be connected to the camera ground. This enables the use of silicon and gallium arsenide (hole counting) and cadmium telluride (electron counting) as sensor materials.

A DC-DC convertor isolates the low voltage power supply used by the switch-mode convertor to produce the high voltage. The isolated low voltage also supplies the microcontroller and the other circuits involved in control and monitoring of the switchmode supply.

The switchmode convertor generates pulses at a fixed frequency that turn a power transistor, in series with the inductors, on and off. The effect of switching current on and off through the inductors is to evoke a high voltage from the "back EMF" of the inductors. This pulsing voltage is rectified and smoothed before appearing at the high voltage connector. The duty cycle, or pulse width, is varied by the controller in a feedback loop. Changing the pulse width changes the output voltage from the inductors.

The setpoint or target voltage for the switchmode convertor is generated by the microcontroller chip, using a DAC output. By changing this voltage, the microcontroller programs the switchmode convertor to produce the required bias voltage. The microcontroller contains flash memory with firmware, and it has an RS232 interface through which it receives commands from the motherboard.

The motherboard uses RS232 asynchronous serial signalling to send commands to and receive responses from the high voltage microcontroller. Serial communication passes through opto-isolator chips, which allow digital signals to pass even though the microcontroller can be at a high voltage (hundreds of volts negative) relative to the camera ground, depending on how the bias supply is connected to the Medipix chips.

DC power to the high voltage board can be supplied through the terminal connector next to the RS232 connector. It is also possible to supply power via the 10-wire flat cable to the RS232 connector, though this may not be able handle the current drawn by a Peltier device running at high levels.

5.2.2 Cooling system functions

The 12 volt supply on the non-isolated supply, from the motherboard (or optional on board connector) is passed to the two-pin fan connector to drive the cooling fan.

A power transistor, with a feedback loop on its output voltage, supplies current, up to several amps, to a Peltier device. The Peltier device cools the Medipix chip carrier heat sink. The control voltage for the Peltier is set by the microcontroller. The output voltage to the Peltier is measured by an ADC which is monitored by the microcontroller. This allows the microcontroller to program a desired voltage to the Peltier device, according to the target set by the motherboard through the RS232 serial interface.

An LM35 temperature sensing chip, enclosed with (or fitted to) the Medipix chip carrier, receives power from the high voltage board and returns a voltage level of 100 mV per degree Celsius. This voltage is read by the ADC (which has four input channels available) and is reported, on request of the motherboard, by the microcontroller.

Communication between the microcontroller and the cooling system uses I^2C (Inter-IC), a serial digital protocol, via an optoisolator chip.

5.3 Medipix chip carrier boards

Medipix chips are glued to a chip carrier, a printed circuit board, sometimes singly. Often several chips are combined into a single imaging module. The chips are said to have been “tiled” into a rectangular array to create a large sensitive area in an x-ray detector.

Chip carriers are designed and supplied by CERN, by Panalytical, and by the MARS project. Wire-bonding of the Medipix chips, including those on the MARS design, is performed at CERN and other labs in Europe.

Apart from the CERN designs, there are several other designs of chip carrier for Medipix2 and Medipix3 chips. Each design supports one or more Medipix chips which have their input/output pads wire-bonded to printed circuit tracks on the board. The top surface of the sensor layer (or layers) is attached by fine wires to a pad connected to the high voltage bias supply. The chip carrier has a connector for the main Medipix signals, and some way of passing the high voltage bias supply onto the board. There are passive components (resistors, capacitors and inductors), and there may also be active electronic devices (voltage regulators) and LEDs.

The following subsections give an overview of the various kinds of chip carrier for Medipix.

5.3.1 CERN Medipix2

One version of chip carrier for the Medipix2 MXR and Timepix is available. There is only one chip fitted to this board. It has a mini-BNC style connector for the high voltage supply, while the Medipix signals are carried on a 68-pin VHDCI plug, also known as a SCSI connector. Standard SCSI cables are used to connect the chip carrier to the MARS camera.

5.3.2 Panalytical Medipix2

This Dutch company, which works in association with the Netherlands nuclear research organisation NIKHEF, designed its own chip carrier for MXR. It is used in commercial spectrometry instruments. The chip board is similar in electrical design to the CERN board, but includes inductors on some LVDS circuits and has a different physical shape. It uses the same SCSI connector. It has optional voltage regulators, but these are not used with the MARS camera.

5.3.3 NIKHEF Quad Medipix2

Four MXR chips are tiled into a square array under a single sensor chip. Pixels along the border between the four ASICs are three times normal size. Signalling is done using the daisy-chain capability of Medipix, so that no extra signals are required on the connector. This board is supported by the IEAP USB readout and the NIKHEF MUROS and MUROS-2. It is not supported by the MARS camera.

5.3.4 MARS linear hex Medipix2 and Medipix3

The first MARS chip carriers have space for a single row of up to six Medipix chips. Only one of these chip carriers, for Medipix2, is in use. It has two MXRs with cadmium telluride sensors; each of the chips has its own sensor layer. The MARS chip carrier has no voltage regulators and requires the correct voltages to be supplied by the camera. The connector is a high density Samtec design with 180 signal lines, and two sets of 12 heavy duty earth lines.

5.3.5 MARS hex Medipix3

The MARS chip carrier for Medipix3 has space for two rows of three Medipix chips. Figure 5.3 shows a unit with four of the possible chips fitted, with a single piece silicon sensor. There have been three revisions of this board. At this time there are nine boards with four Medipix3 v3.0 chips fitted; all have single piece silicon sensors. Three boards had single Medipix3 v3.0 chips with GaAs sensors; these are currently being reworked. Finally, one board was fully populated with six Medipix3 v3.0 chips and a single cadmium telluride sensor. Of the nine boards with four chips each, five of the boards have the chips fitted at the physically lower end (where the chips are numbered from 0 to 3). The other four have their chips fitted at the upper end, using chip positions 2 to 5. This choice of assembly was not anticipated but is now supported by a setting on the MARS camera. The board uses the same Samtec connector as the Medipix2 hex board. The high voltage bias is supplied by a separate lead soldered to the side of the chip carrier. The most recent version of the board has an LM35 temperature sensor soldered to it. It has data lines for all 8 channels of the data bus for the four lower chip positions. There

Figure 5.3: *Left* Hex silicon Medipix3 chip carrier with quad silicon Medipix3 fitted as seen when sensor side unprotected by acetal block. *Right* The same chip carrier seen from the back side, fitted into the protective block. The metal heatsink deep in the block has a patina of conductive thermal grease. When installed in a camera, this surface is in contact with the underside of the Peltier heatsink plate. The 180 pin Samtec plug is visible on the right of the printed circuit board.

are no voltage regulators on the board.

5.4 Mechanical hardware

The MARS camera is designed to be a complete x-ray imager in a compact portable enclosure. It has a mounting plate, threaded for four thumbscrews, sized to fit onto a camera mount in the MARS CT scanner. It has a socket for an LTC miniature locking bayonet socket with a 2-wire 12 volt DC power connection, and an access port for a standard Ethernet cable with RJ45 jack as well as the 10-pin Berg header for the diagnostic RS232 serial cable. There is a rectangular aperture through which x-rays enter on the front face of the case. A 12 volt cooling fan and heatsink is thermally connected to a Peltier device that cools the Medipix chip carrier via metal heat sink plates. The Medipix chip carrier is assembled into a light tight unit (a black acetal box) in thermal contact with the heat sink plates. This, combined with the Peltier device and fan, is attached by screws through the front plate at the same end as the x-ray aperture. The painted aluminium case has a set of threaded PEM pcb standoffs into which the two printed circuit boards - the high voltage board below, the motherboard above - are screwed. There is a ventilating grille in the end of the case close to the Peltier transistor on the high voltage board. Air is forced by the cooling fan along the lower side of the motherboard and passes the high voltage board. There is an option to mount the Peltier transistor directly onto the case in the centre of the ventilating grille.

Figure 5.4: The MARS chip carrier enclosure is made of acetal, dyed black for light tightness

Chapter 6

Camera firmware

Contents

The camera firmware, running on the 32-bit Nios2 CPU in a part of the 32 megabytes of RAM, uses an executive loop structure that polls two input interfaces for commands: the network interface (Ethernet with UDP/IP), and the diagnostic RS232 interface (plain ASCII) . When a command has been recognised it is processed until completion, and a response is transmitted back to the interface from which the command was received. There are a couple of exceptions to this simple statement. First of all, opening the shutter with an exposure time of more than 100 milliseconds allows command polling to continue. Second, diagnostic logging enables the display of progress information on the diagnostic RS232 interface during the processing of a command.

6.1 Nios2

This "soft" CPU, implemented in dynamically loaded digital logic on the Altera FPGA, is a Reduced Instruction Set Computer (RISC) processor with fixed width 32-bit instructions. It has an instruction cache that improves the rate of execution of programs that would otherwise be slowed down by accesses to the DDR RAM chip. Data caching is possible but is not used in the current firmware. Input and output are memory-mapped, meaning that all hardware access is done by reading or writing to an address in the CPU address space. The clock speed is 50 MHz, which means that the fastest machine instructions run in a single "machine cycle" of 20 nanoseconds. Any access to a memory address, such as an input or output address, adds machine cycles to the processing time of a machine instruction.

Executable code for the Nios2 is generated from C source files by a version of the GNU C-compiler *gcc*. This version is supplied by Altera as part of the Nios2 Software Development Kit or SDK. Altera supplies a library of functions to allow access to the various input and output devices used by the camera firmware. This includes devices that have been developed by the MARS project for Medipix communication, such as the clock generator and counters.

6.2 Device interfaces

For each of the hardware subsystems, there is a function in the firmware that provides access through the hardware-software interface of the Nios2 and FPGA to that device. The following subsections introduce those low level device interface functions.

6.2.1 Gigabit Ethernet

Gigabit Ethernet network operations includes setup of the MAC, Ethernet, IP and UDP protocols, and the reception and transmission of packets. They are handled in functions supplied by IFI, the developer of the Ethernet MAC firmware that is installed in the FPGA.

6.2.2 RS232

Asynchronous serial RS232 communication via FPGA logic gives access to two devices: diagnostic commands from an external terminal, and the high voltage board microprocessor. Access these devices is provided in the Altera device library under the names "/dev/ExtSerial" and "/dev/HighVoltageSerial".

The diagnostic command interface, used for initial configuration of a new MARS camera, and for debugging during development, is accessed via a 10-pin Berg header located next to the Ethernet jack. A Berg-plug to 9-pin D connector is available to allow a PC with USB-to-RS232 convertor, running terminal emulation software, to connect and communicate with the camera. The baud rate is 115200 bits per second. Plain ASCII text is used to specify commands and to send responses.

The high voltage board interface carries commands from the motherboard to the high voltage board microcontroller, and responses from the HV board. A 10-wire flat cable connects the two Berg headers. It also connects the 12 volt DC supplies between the two boards. The baud rate is 1200 bits per second.

The high voltage board microcontroller interprets plain ASCII text commands to: switch the bias voltage generator on and off; to set its target voltage and read its actual output; to set the Peltier device voltage and read its output; and to read the temperature reported by the LM35 sensor on the chip carrier.

6.2.3 Serial Peripheral Interconnect (SPI)

SPI is a commonly used serial bus protocol for microcontrollers to communicate with "smart" integrated circuits. The MARS camera has four types of SPI device on two separate SPI buses. On one bus there are five electronically variable potentiometers that are used to set the programmable power supplies. On the other bus are four DACs, an ADC, and a serial-to-parallel convertor. Clock and data signals for the buses are generated in software by "bit-bashing", which means that clock signals are generated by relatively slow write operations to one bit of an output port. Data output and input is coordinated bit-by-bit by the bit-bashing algorithm. Compared to a hardware solution with automatic clock pulse generation, the process is slower.

6.2.4 Programmable power supplies

There are three programmable power supplies. Two receive an input regulated voltage from a linear "pre-regulator" that has a programmable output voltage. The third receives its input from the motherboard's 5 volt supply. The operating point of the three supplies is set by a software controlled potentiometer accessed via SPI.

6.2.5 Motherboard DACs

The four DACs supply the `ExtDAC` and `ExtBandgap` analog signals to each of six Medipix chips. They are accessed indirectly using the SPI bus, over which the DAC address and the value to be programmed is passed.

6.2.6 ADC

The ADC reads a voltage that is passed, through two analog multiplexors, from one of 15 different sources. Six of the sources are the `DAC_Out` signals from six Medipix chips. The other sources are the feedback voltage and current signals from the three programmable power supplies, and the output voltage of the regulator that pre-regulates two of those three supplies. The multiplexor address is sent over an SPI bus, and the ADC is started. When the ADC indicates that it has completed conversion, its output is read via SPI.

6.2.7 Medipix control lines

An SPI serial-to-parallel convertor supplies the ADC_Enable signal, and two 3-bit addresses, to the two ADC multiplexors. It also produces the Reset, M0, M1 and Polarity signals for Medipix2 chips. M0 and M1 are interpreted as MatrixFastClear and CounterSelect by Medipix3 chips.

A parallel output port on the FPGA supplies Shutter, PHYTER_reset, and Medipix3 TestPulseSwitch signals.

6.2.8 Medipix serial communication

FPGA logic modules, custom designed for Medipix, are assigned for each of six Medipix chips. There is a single clock generator, an output shift register with associated control lines, and an input shift register. In addition there are single input and output lines accessed through conventional parallel ports.

The clock generator, running at 50 MHz, is shared: its output is replicated to all six chips. For both transmission and reception the software can select between the 50 MHz hardware clock or bit-bashed mode. Bit-bashing is used for operations where simultaneous input and output is required (e.g. Medipix2 FSR write/read, which returns the identifying fuses).

For data transmission to Medipix there is a 32-bit parallel to serial convertor. This provides the Enable_Out, Clock and Data signals to the Medipix chip via LVDS level convertors. The FPGA logic requires that a protocol be followed to preload the shift register through a parallel output port, before initiating the data transfer. The clock and data lines can be driven directly through a parallel output port, allowing bit-bashed data transmission.

For data reception from Medipix there is a 32-bit serial to parallel convertor. This receives its clock signal from the Medipix Clock_Out, and data from Data_Out. The Enable_Out signal from the Medipix chip is available at a parallel input port and is used to check that communication with the Medipix chip is operating normally. Copies of the clock and data lines are also available at the parallel port so that bit-bashed data reception can be performed.

6.2.9 Flash memory

Read, write and erase functions for the Altera-compatible EPCS flash memory are available through the Altera device library using the device "/dev/epcs_flash_controller_0". Flash memory is used to store configuration settings, such as the Medipix chip carrier type and the motherboard revision number. The memory chip also contains the FPGA configuration, and the Nios2 firmware.

6.3 Command handler

The MARS camera firmware is a relatively simple "reactive" program with only a single process that runs all the time after "boot up" has completed. During boot up essential variables are loaded, the serial communication interfaces are configured, and the Gigabit Ethernet system (including the physical interface or PHYTER) are reset and programmed. Once boot up completes a so-called "executive command loop" is entered. This is simply an endless program that checks each of the possible command sources to see if a complete and valid command has been received, and performs the associated function calls for each of the possible commands (or displays an error message).

The executive command loop polls the Ethernet receiver and the diagnostic RS232 interface in turn. A command from Ethernet is contained completely in one packet. A diagnostic command arrives one ASCII character at a time, and the full command is recognised when a carriage-return is received. The Ethernet packet handler performs several functions and is described in greater detail next.

In the following subsections each of the available MARS commands is described, as well as the key diagnostic RS232 commands.

6.3.1 Ethernet packet handler

There are three "layers" in the processing of Ethernet packets.

The lowest layer is necessary to allow the initial setup of an Ethernet connection and uses the standard address resolution protocol ARP. This is a method by which two devices get to know each other's Ethernet MAC address: the 48-bit integer that is in principle unique to each Ethernet device in the world. ARP is used between the PC and MARS camera when the camera is plugged into the PC's network.

The next layer, part of the IP protocol, is used to verify that the camera has a valid IP address and that it is "on" the network. This is verified by checking for and responding to the `ping` command, part of the internet control message protocol, ICMP.

The ARP and ICMP layers are handled automatically by the software that was supplied by IFI with the Ethernet MAC logic for the FPGA.

The final layer handled by the packet hander is the user datagram protocol, UDP. UDP/IP (i.e. UDP messages inside IP protocol messages) is a simpler protocol than TCP/IP: the protocol on which the Internet is built. TCP/IP includes functions to guarantee the delivery and receipt of messages containing one or more packets; UDP does not offer guarantees and only supports a single packet at at time (approximately 1500 bytes on Ethernet). The advantage of UDP is that it is simpler to process than TCP. UDP does not require timeouts, acknowledgements or retries. It also uses less overhead bytes per message.

When a UDP message is detected by the Ethernet packet handler, it is passed to the command handler to be interpreted and handled. A MARS command is identified by a 4-byte code (in ASCII) at the front of the message. The MARS commands understood by the camera are `helo`, `peek`, `poke`, `wrib` and `reab`. They are described in the following sections.

6.3.2 helo

Abbreviated from "hello", this message provides a straightforward indication that a MARS camera is present. The camera replies with an `ack` message.

6.3.3 peek

Named after a command that used to be offered in BASIC interpreters to allow a value to be read directly out of memory, this command has one parameter - a numerical address - to identify the value that the PC requires the camera to return. Table 6.1 contains a list of the allowed addresses and describes the meaning of the associated values. Addresses starting with "0x" are in hexadecimal.

6.3.4 poke

Named after a BASIC command that writes a value to memory, this command has two parameters: an address, and the value to be written to that address. The command has two kinds of effect. Firstly, it allows a value to be set in the camera, for example the shutter time. Alternatively, it triggers a command to be performed by the camera, for example to open the shutter (for a length of time already set).

Table 6.2 shows the addresses and the effects of the possible values. The expression "data & 0x01" means the logical result of testing the value of the lowest bit of "data".

6.3.5 reab

The name of this command is a combination of "read" and "buffer". While `peek` reads a single 16-bit number, `reab` reads as much data as will fit into an Ethernet packet (approximately 1400 bytes) from a buffer area in camera memory. There is a buffer area for each of six Medipix chips, and there are different zones within a buffer area to store various kinds of Medipix data. A similar scheme applies for the `wrib`, "write buffer" command (see following section).

Table 6.3 lists the zones in the buffer for the first Medipix chip, starting at address 0x0f0000, where the prefix 0x means a hexadecimal address. The second to sixth chips use the address 0x1f0000, 0x2f0000 up to 0x5f0000.

The `reab` command has two parameters: the buffer address, and the length of the returned data, i.e. the number of bytes to read. The maximum allowed value

Table 6.1: Addresses and the meanings of their values for the `peek` command

Address	Value
64	ADC reading of chip 0 DAC out
60	… chip 1 DAC out
72	… chip 2 DAC out
76	… chip 3 DAC out
80	… chip 4 DAC out
80	… chip 5 DAC out
128	high voltage feedback
132	high voltage set point
136	set shutter time
144	GIC set value
148	software version
160	chip carrier and chip type
164	set test pulse count
168	Peltier set point
172	chip carrier temperature
0x0ff000	Medipix2 chip 0 type
0x1ff000	… chip 1 type
0x2ff000	… chip 2 type
0x3ff000	… chip 3 type
0x4ff000	… chip 4 type
0x5ff000	… chip 5 type

is 1416 bytes.

6.3.6 wrib

The name of this command is a combination of “write” and “buffer”. There are two ways in which this command works. For the Medipix3 OMR, DAC and CTPR registers, the register data is first copied to the buffer zone for this register. Then an immediate write of the data is done, from the buffer to the associated Medipix3 chip. The chip number is obtained from the buffer address as explained in the next paragraph. For the matrix data for both Medipix2 and Medipix3, and for the Medipix2 FSR, no immediate write takes place. Instead, the mechanism based on `poke`, above, is used by the PC after first passing the data to the buffer. This takes slightly more time.

Table 6.4 lists the zones in the buffer for the first Medipix chip, starting at address 0x0f0000, where the prefix 0x means a hexadecimal address. The second to sixth chips use the address 0x1f0000, 0x2f0000 up to 0x5f0000.

6.3.7 Diagnostic commands

Table 6.5 lists diagnostic commands to enable logging, and to set and store configurable settings to define the Medipix type, chip carrier type, and motherboard revision. With the exception of the `configstore` command, the commands expect a parameter with one of the tabulated values.

6.4 Summary

In this chapter an overview of the camera firmware has been given. Instead of the motherboard including a physical microprocessor, its Altera FPGA implements the dynamically loaded logic of a complete 32-bit microcontroller CPU. The CPU firmware is loaded from flash memory at boot time, and after initialisation the program waits for commands from Gigabit Ethernet and RS232. MARS commands are transported over Gigabit Ethernet using UDP over IP, while diagnostic commands are in plain ASCII over an RS232 interface.

The next chapter introduces the PC software library through which application programs access the MARS camera.

Table 6.2: Addresses, their values and actions for the `poke` command

Address	Value	Action
0x00		Set DAC for chip 0 external input
0x04		… 1 external input
0x08		… 2 external input
0x0c		… 3 external input
0x10		… 4 external input
0x14		… 5 external input
0x18		… 6 external input
132		high voltage set point
136		shutter time
140		*Medipix2 camera control command*
	data&0x01	open shutter for the set amount of time
	data&0x02	reset Medipix chips
	data&0x04	write the FSR for chip `MPXChipNumber`
	data&0x08	read matrix into buffer from chip `MPXChipNumber`
	data&0x10	write matrix from buffer to chip `MPXChipNumber`
144		*Medipix2 GIC command*
	data&0x01	set polarity to 0 or 1
	data&0x02	set CST to 0 or 1
148		*Medipix3 camera control command*
	data&0x10	perform matrix fast reset
	data&0x20	reset Medipix chips
	data&0x40	read counter C0 or C1
	data&0x80	”dummy read” of counter C0 or C1
152		Set `MPXChipNumber` and `MPX3Counter`
164		number of test pulses
168		Peltier target (millivolts)
0x0f0060		
0x1f0060		
0x2f0060		
0x3f0060		
0x4f0060		
0x5f0060		*set ChipNr = (address-0x0f0060)/0x100000)*
	data&0x0001	write OMR(ChipNr) from buffer
	data&0x0002	write DACs(ChipNr) from buffer
	data&0x0004	write CTPR(ChipNr) from buffer
	data&0x0040	read OMR(ChipNr) into buffer
	data&0x0080	read CTPR(ChipNr) into buffer
	data&0x0400	write Counter0(ChipNr) from buffer
	data&0x0800	write Counter1(ChipNr) from buffer

Table 6.3: Addresses and their actions for the `reab` command

Begin address	End address	Value
		Medipix2 read buffer
0x050000	0x06c021	read "length" bytes from matrix zone of buffer
0x070000	0x0f001f	read 32 bytes of data from FSR zone of buffer
		Medipix3 read buffer
0x080000	0x0affff	read "length" bytes from matrix zone of buffer
0x0f0000	0x0f001f	read 32 bytes of data from OMR zone of buffer
0x0f0020	0x0f003f	read 32 bytes of data from DAC zone of buffer
0x0f0040	0x0f005f	read 32 bytes of data from CTPR zone of buffer

Table 6.4: Addresses and their actions for the `wrib` command

Begin address	End address	Value
		Medipix2 read buffer
0x050000	0x06c021	write "length" bytes into matrix zone of buffer
0x070000	0x0f001f	write 32 bytes of data into FSR zone of buffer
		Medipix3 read buffer
0x080000	0x0affff	write "length" bytes into matrix zone of buffer
0x0f0000	0x0f001f	copy 32 bytes to OMR zone, write immediately
0x0f0020	0x0f003f	copy 32 bytes to DAC zone, write immediately
0x0f0040	0x0f005f	copy 32 bytes to CTPR zone, write immediately

Table 6.5: Diagnostic RS232 interface commands

Command	Parameter	Effect
chiptypeset	n	*n is one of the following values*
	2	Medipix2 on single or multi-chip carrier
	3	Medipix3 single (CERN board)
	4	Medipix3 quad (MARS board)
	5	Medipix3 hex (MARS board)
	6	Medipix3 “top” quad (MARS board)
pcbrevisionset	n	*n is one of the following values*
	1	Revision B motherboard
	2	Revision C motherboard
mpvariantset	n	*n is one of the following values*
	0	Medipix3 version 3.0
	1	Medipix3 version 3.1
	2	Medipix3 version 3.2 (RX)
configstore		Save settings to flash
log	0 or 1	1 to enable logging, 0 to disable
debug	”on” or “off”	”on” to add extra info to log

Chapter 7

Camera PC software

Contents

This chapter explains the structure of the PC software, its design considerations, and summarises the function calls through which it is used. It includes the user interface specification for a command line program that allows the basic camera functions to be tested, and an image to be acquired under a set of pixel mask values and DAC settings.

The MARS camera library, `libmars-camera`, is a library of public (and private) functions that contains detailed internal specifications of Medipix and the associated hardware, firmware and network protocol. It makes the functions of Medipix and the camera available through an application programming interface or API. API functions are callable from Python and from native C programs.

The MARS camera uses standard Gigabit Ethernet with IP networking, and is easy to connect to a PC that has an Ethernet interface. In theory, any program can communicate directly with the camera, but this would only be possible if such a program contained detailed internal knowledge of Medipix and of the proprietary

MARS camera UDP/IP protocol. It would also need to be kept up to date as new versions of Medipix, the Medipix chip carrier, or the camera itself are released. Instead of all programs having to carry this burden, `libmars-camera` "hides" the information. Programs written in C or Python, by calling the API functions in the library, automatically invoke the low level algorithms needed for Medipix control and communication.

The following section identifies the various kinds of API function, and tabulates the error return codes which can occur.

7.1 API functions

The API functions are listed in table 7.1. If an error occurs, the nature of the error is encoded in an error number listed in table 7.2. There are functions to: Connect and disconnect with the camera; reset the Medipix chips; load an equalisation mask; set and get chip and board attributes; load the Medipix DACs; and acquire an image. The functions are explained further in the following sections.

7.2 Connecting and disconnecting

Function `find()` attempts to communicate with the camera by using a `helo` message. If the camera responds, the type and number of chips is identified by a sequence of further commands. `close()` releases the network socket which was used to set up the connection.

7.3 Reset

Function `resetChip()` resets all Medipix chips in the camera. DACs and equalisation masks must be reloaded.

7.4 Loading the equalisation mask

Function `loadConfig()` readies a set of 64k pixel configuration register settings for loading, and sends the serialised data to the camera, followed by the command to install the mask into a Medipix chip. The function `downloadMask()` requests the camera to read the mask out of a Medipix chip, transmit it back to the PC, and deserialises the data. The function `getImage()` is used to copy the downloaded data into the calling program, so that it can be compared with the uploaded data to check for matrix memory errors. Function `loadConfigFile()` reads pixel configuration settings from a named file, then follows the same steps as `loadConfig()`.

Table 7.1: Camera API functions in Python and C

Python	C
find()	camera_find()
resetChip()	camera_reset()
close()	camera_close()
loadConfig()	camera_load_mask()
loadConfigFile()	camera_load_mask_from_file()
downloadMask()	camera_download_mask()
setAttribute()	camera_set_attrib()
getAttribute()	camera_get_attrib()
setChipAttribute()	camera_set_chip_attrib()
getChipAttribute()	camera_get_chip_attrib()
setDac()	camera_set_dac()
getDac()	camera_get_dac()
acquire()	camera_acquire()
getImage()	camera_get_frame()
getImageSize()	(no equivalent in C)
	Shortcut function calls
setHV()	camera_set_attribute(...,"hv",...)
getHV()	camera_get_attribute(...,"hv")
setPolarity()	camera_set_attribute(...,"polarity",...)
getPolarity()	camera_get_attribute(...,"polarity")
setChipType()	camera_set_attribute(...,"type",...)
getChipType()	camera_get_attribute(...,"type")
getChipCount()	camera_get_attribute(...,"chips")

7.5 Motherboard and chip attributes

An “attribute” is the name of a feature of a Medipix chip, or on the motherboard, that can be given a value or that may have its current value read.

Function `setAttribute()` is used with one of the named attributes, from table 7.3, to set a value controlled by the camera motherboard. Function `getAttribute()` returns the value for a named attribute from the motherboard.

The function `setChipAttribute()` loads a value, from table 7.4, to the named attribute of a specified single Medipix chip. Function `getChipAttribute` retrieves the value of an attribute from a single chip.

Table 7.2: API function error codes

Error nr	Interpretation
8	Function argument is not valid
37	Allocation of memory failed
41	Network command did not receive a response
42	Network response not of correct size
43	Camera did not accept the command
44	Camera did not accept index number
45	Internal error during chip identification
46	Too much data received in stream

Table 7.3: Camera motherboard attributes. The attribute name is given in the call to `setAttribute()` or `getAttribute()` to change or to retrieve a setting that is relevant to the motherboard or that (except for `dacN`) affects all the Medipix chips.

Attribute	Description
	Can be used with `set` *and* `get`
`dacN`	External DAC setting for chip N=0...5
`hv`	High voltage board setting in mV
`polarity`	Set polarity bit (Medipix2) to 0 or 1
`tpulse`	Set the number of test pulses (Medipix3)
`peltier`	Peltier device supply setting in mV
	Used with `get`
`adcN`	Measure the DAC output from chip N=0...5
`chips`	Obtain the number of Medipix chips
`temp`	Obtain LM35 temperature in units of 0.1 deg C
`carrier`	Obtain chip carrier type
`swversion`	Obtain camera software version number

Table 7.4: Medipix chip attributes. The chip number is included in the call to `setChipAttribute()` or `getChipAttribute()`. Only a single chip is affected by the function call. Note that some of the OMR settings should not be altered.

Attribute	Description
	Can be used with `set` *and* `get`
`dac`	External DAC setting for chip N=0...5
`ctpr0`	Test pulse register, 1st 64 bits(Medipix3)
`ctpr1`	Test pulse register, 2nd 64 bits (Medipix3)
`ctpr2`	Test pulse register, 3rd 64 bits (Medipix3)
`ctpr3`	Test pulse register, 4th 64 bits (Medipix3)
	Used with `get`
`adc`	Measure the DAC output from chip N=0...5
`type`	Obtain the Medipix chip type
`fuses`	Obtain the Medipix chip fuses
	Medipix3 OMR bits, used with `set` *and* `get`
`CRW`	Continuous read/write. Always set to 0.
`Polarity`	Charge pulse polarity: 0=positive (holes), 1=electrons
`PS`	Parallel or serial output: 0=serial, other values not used
`Enable_TP`	Test pulses: 0=no, 1=enabled
`CountL`	Counter length: 0=1 bit, 1=4 bit, 2=12 bit, 3=24 bit
`ColumnBlock`	Subset of columns to read out. Always set to 0
`ColumnBlockSel`	Enable column subset. Always set to 0
`RowBlock`	Subset of rows to read out. Always set to 0
`RowBlockSel`	Enable row subset. Always set to 0
`EqualizeTHH`	Counter C1 equalization: 0=C0, 1=C1
`ColorMode`	Spectroscopic mode: 0=no, 1=yes
`EnablePixelCom`	Charge summing mode: 0=no, 1=yes
`SenseDAC`	Enable analog feedback of DAC: 0=no, n=DAC code nr
`ExtDAC`	Replace DAC with external source: 0=no, n=DAC code nr
`ExtBGSel`	Replace bandgap reference with external source: 0=no, 1=yes

7.6 Medipix DACs

Tables 7.5 and 7.6 list the DAC names and code number for Medipix2 and Medipix3.

Function `setDac()` loads the specified value into a named DAC. For Medipix3 only, the current value of a named DAC can be retrieved using `getDac()`.

On Medipix2, the code number of a DAC which is be put into feedback mode, so that its output can be sensed with an ADC, is specified by calling `setDac()` with the name `SenseDAC` and the code number. Likewise for specifying the code number of a DAC that is to be overridden by a DAC from the motherboard: call `setDac()` with the parameter name `ExtDAC`, and the code number.

The trailing entries in the two tables are the names and codes of internal signals in Medipix2 and Medipix3 that are not programmable, but that can monitored in the same way as a DAC, and that can be overridden by the external DAC source.

Table 7.5: MXR DACs. Specify a name and target value in the `setDac()` function call to program the DAC. Supply a code value from the right hand column using the `SenseDAC` or `ExtDAC` parameter in `setDac()` to specify a DAC to be sensed or to be overridden. The internal signals, last in the table, are not programmable but are able to be sensed or overridden.

Name	Code
`IKrum`	15
`Disc`	11
`Preamp`	7
`BuffAnalogA`	3
`BuffAnalogB`	4
`DelayN`	9
`THL`	6
`THLFine`	–
`THLCoarse`	–
`THH`	12
`THHFine`	–
`THHCoarse`	–
`FBK`	10
`GND`	13
`THS`	1
`BiasLVDS`	2
`RefLVDS`	14
Internal signals can be sensed or overridden	
`BiasDAC`	0
`BiasOutStage`	5
`vbgOnChip`	8

Table 7.6: Medipix3 DACs. Specify the DAC name and target value in the `setDac()` function call to program the DAC. Supply a code value from the right hand column, using the `SenseDAC` or `ExtDAC` attribute in `setChipAttribute()`, to specify a DAC to be sensed or to be overridden. The internal signals, last in the table, are not programmable but are able to be sensed or overridden.

Name	Code
Threshold0	1
Threshold1	2
Threshold2	3
Threshold3	4
Threshold4	5
Threshold5	6
Threshold6	7
Threshold7	8
Preamp	9
Ikrum	10
Shaper	11
Disc	12
Disc_LS	12
ThresholdN	14
DAC_pixel	15
Delay	16
TP_BufferIn	17
TP_BufferOut	18
RPZ	19
GND	20
TP_REF	21
FBK	22
Cas	23
TP_REFA	24
TP_REFB	25
Internal signals can be sensed or overridden	
Band_Gap Output	26
Band_Gap Temperature	27
DAC Bias	28
DAC cascode bias	29

7.7 Image acquisition

To take an image, the function `acquire()` is called with the exposure time in seconds as a parameter. The camera opens the shutter signal to the Medipix chips for the programmed time, then closes it. The counter matrix from each of the chips is transferred back to the PC and the data is deserialised. For Medipix2 the pseudo-random binary codes are translated to counts. The image data is stored in memory allocated by the library. An application program copies the data from the library by calling function `getImage()`.

7.8 Camera command line utility

In this section I describe a software tool that I wrote to exercise the most useful camera operations that were available at the time. When I began to list the features I needed in this program, in early July 2011, I had already developed several tools to perform basic testing, and some image acquisition with Medipix2 and Medipix3 chips.

For a year or more I had been writing task-specific scripts in Python. Over time I had also developed two programs in C. One, `dacscan`, performed a rudimentary DAC scan on either a Medipix2 (MXR) or a Medipix3. The other, `marscam`, performed a threshold scan on the two chips types. Neither of the programs was very flexible, though it could access any of the chips in a multi-chip camera. Python scripts, while granting total freedom to access all the camera features available from library `libmars-camera`, were effective, but again lacked flexibility. I wanted a program that would make it easy to specify values for the vast array of configurable settings (including DACs, but also exposure time, polarity, iteration ranges, and more).

The problem I had been working on when I started noting down my requirement for a unified test program (or set of test programs) was that of equalising Medipix3 chips. A list of six programs that I thought would "aid and abet multi-chip image equalisation", from my notebook, is:

1. Faulty pixel (matrix memory) test $-- >$ fault mask
2. DAC scans (including external DAC)
3. Pixel noise analysis (including ThresholdN/DAC_pixel sensitivity analysis)
4. Equalisation
5. Threshold scan (NB: this is looking for 'active pixels', or for 'total counts'; they have different meanings)
6. Imaging (including x-ray tube control) (NB: include test pulses? suppress noise?)

By the end of July 2011 I had implemented all of the above except Equalisation in a single program called `mccli` for MARS camera command line interface. It works only with Medipix3 chips. I gradually enhanced it with more functions in the following weeks. X-ray tube control was not included; I continued to rely on the existing MARS GUI program to turn the x-ray tube on and off.

The following section is taken from a recent version of the user guide. By default, the commands work on the first (or only) Medipix3 chip on a chip carrier. Chips are numbered from 0 upwards.

7.8.1 MCCLI user guide

`MCCLI.EXE` is a command line program which accepts a command and a number of options. Before running it, you need to set the IP address of your computer in the range 192.168.0.xxx (other than the camera's default of 192.168.0.44). By default `MCCLI.EXE` will work with the first chip (chip 0) in a multichip system. It reports the number of chips that it detects when it connects. It is not bulletproof: if you ask for a chip number that isn't present (eg chip 3 on a board that only reports 3 chips) it'll push on and you'll probably see some strange results. It will also report the settings and DAC values loaded to the Medipix3 chip(s).

7.8.2 Operating hints

You need to know that Medipix3 requires that the CAS DAC (dac23) has to be set externally. I use `--extdac=d23:1000` to set it to 1000 mV. I also set the FBK DAC (dac22) to 162 using `--dac=d22:162`. A basic demonstration that a Medipix3 chip is working would be to run the following four commands (using the `--chip n` option to select the upper chips on a multi-chip assembly)

- `mccli memtest`
- `mccli dacscan --dac=d1:0:511:50`
- `mccli acquire --extdac=d23:1000 --dac=d22:162 --dac=d1:0 --eq0:0:31:1 --tally 1`
- `mccli acquire --extdac=d23:1000 --dac=d22:162 --dac=d1:0:511:10 --pixel 16x16+0+0 -- exp 1000 --rep 60`

The first tests matrix write and read. The second tests DAC programming and DACout feedback. The third runs through all possible values of the equalisation DACs with Threshold0 at its minimum value, where there ought to be lots of noise. You should see a bimodal distribution of 32 numbers, starting in the thousands, dropping down to single or double digits, then rising again to thousands. If you see nothing but 0's then you're seeing what I have been seeing on the rev B chip carriers (and the GaAs assemblies).

The fourth command takes a series of 60 1 second exposures and displays the contents of an array of 16x16 pixels starting at the top left corner.

7.8.3 The `memtest` command

Writes a series of ten 12-bit patterns into counter 0 (or counter 1) of every pixel in the matrix. It then reads the matrix out and does a pixel for pixel comparison of the written and read patterns, and reports the number of pixels that are not identical. A perfect result is a column of 0's.

Options supported by memtest are (my comments are in parentheses):

1. `--chip n` (0 based)
2. `--pattern xxx` (where xxx is 3 hexadecimal nibbles. Only this pattern will be tested)
3. `--all` (i.e. all chips. This will fail badly if there aren't 4 chips on a quad, as is currently happening with the rev B chip carrier)
4. `--counter n` (n is 0 or 1 for the Medipix3 counter/matrix 0 or 1)
5. `--o filename` (saves error map to file, 16 bits per pixel)

7.8.4 The `dacscan` command

Requires you to specify a DAC. DACs are specified using the letter "d" followed by the DAC number from 1 to 25. Table 4.4 lists the Medipix3 DAC names and numbers. As well as the DAC name, a range of values is given as an "iterator", the specification of a sequence of values to be written to the DAC. The command reports the DACout value in mV for each of the programmed values. The syntax for a DAC range is `-- dacnr:start:end:step`. For example, to do a DAC scan on every possible value of Threshold0 (which is numbered DAC1 and happens to be a 9-bit DAC) you would type `mccli dacscan --dac=d1:0:511:1`. If instead you intend to use the external DAC to override the internal source in the range 0 to 1600 mV with 100 mV steps, you would type `mccli dacscan --extdac=d1:0:1600:100`

Options supported by `dacscan` are:

1. `--chip n` (0 based)
2. `--dac=dacnr:start:end:step` (units are DAC values)
3. `--extdac=dacnr:start:end:step` (units are mV)
4. `--peltier n` (Peltier device voltage; units are mV)
5. `--hv` (bias voltage; units are V)
6. `--all` (all chips, same proviso as `memtest`)

7.8.5 The `acquire` command

Makes an exposure after uploading values to the DACs and setting the other variables such as Peltier, HV, Polarity, etc. You can take a series of exposures with identical settings using `--rep n`. By default the pixel configuration matrix is loaded with 0's (but can be changed using `--eq0` or `--eq1`). After an exposure, the counters are read back. They can be saved to a file (using the `-o` option), displayed (using `--pixel n1xn2+n3+n4`) or tallied (`--tally n`). Typically you would set DACs of importance to a specified value, but if you specify a range it will iterate over the range, taking an exposure for each value.

Options supported by `acquire` are:

1. `--chip n`
2. `--all (all chips, see proviso for memtest)`
3. `--dac=dacnr:dacval` (single DAC value)
4. `--dac=dacnr:start:end:step`
5. `--extdac=dacnr:mV`
6. `--extdac=dacnr:start:stop:step`
7. `--eq0=eqval` (sets all equalisation DACS on all pixels to eqval)
8. `--eq0=start:stop:step` (iterates the equalisation DACS on all pixels from "start" to "stop" by "step")
9. `--eq1=eqval` (same as –eq0 but for counter 1)
10. `--peltier n` (Peltier device voltage; units are mV)
11. `--hv n` (bias voltage; units are V)
12. `--polarity n` (n is 0 or 1)
13. `--csm n` (Charge summing mode; n is 0 or 1)
14. `--gain n` (Pixel gain mode; n is 0 or 1)
15. `--exp n` (exposure time in ms)
16. `--rep n` (number of repetitions of the acquisition
17. `--pixel n1xn2+n3+n4` (shows values of a subset of n1xn2 pixels, starting at row n3, column n4, using 0 based numbering from 0 to 255)

18. `--tally n` (shows tally of the number of pixels that have a count equal to or greater than `n`)
19. `--counter n` (counter number 0 or 1, 0 by default)
20. `-o filename` (saves counter matrix to file, 16 bits per pixel)

7.9 Summary

In this chapter the library of PC functions available to programs written in C or in Python have been outlined. The chapter concluded with the description and user guide of a simple command line PC program for camera testing and basic image acquisition.

The next two chapters report observations made using `mccli` on MARS cameras. The first is an investigation of aspects of Medipix3 equalisation. It is followed by a chapter on some tests of Medipix3 charge summing mode.

Chapter 8

Medipix3 threshold equalisation

Contents

Aspects of the problem of equalising the Medipix3 threshold detectors are described in this chapter. Discussion focusses on the use of noise from the pixel preamplifiers to act as reference signals for the equalisation process. Some observations are presented from six Medipix3 chips on the Hex CdTe camera.

Random variations in the performance of pixel threshold detectors are a well known characteristic of photon counting radiation detectors. For this reason, it is normal to include adjustable corrections to each threshold detector in each pixel of these detectors. The problem of finding the optimum correction for each of tens of thousands of pixels is not straightforward, based on experience of Medipix3 in the MARS project.

Several methods have been tried, during the evolution of Medipix, to facilitate the equalisation task. Equalisation is the process of finding the best value of the equalisation DAC for each pixel in a Medipix chip, and of the global DACs that modulate the pixel equalisation DACs (`THS` in Medipix2, `DAC_pixel` and `ThresholdN` in Medipix3).

8.1 Medipix threshold detectors

The Medipix threshold detector is a zero-crossing detector, sensitive to a change in direction of current at its input. When the current changes from positive to negative, or from negative to positive, the detector output changes state. In the quiescent state (the state when no pulse is present, and the pixel electronics have stabilised after the most recent pulse) every pixel should have the same, small (of the order of nano amps), non-zero current flowing from its front end circuitry. The global threshold DAC `Threshold0` needs to be set to a certain level, based on photon energy, in order to detect photon charge pulses that conform to that energy. When a photon of a certain energy stimulates a pixel, ideally all pixels would behave identically: either the threshold will not be met and no trigger occurs, or the threshold is met and a count is triggered. In reality, the quiescent current in each pixel is different, due to random variations in front end circuits caused by slight random variations during chip manufacture. For the same reason the absolute sensitivity of each threshold detector is also different.

In the absence of equalisation, each pixel responds in its own way to charge pulses due to these random variations. Depending on the pulse direction, some pixels may never cause their detector to trigger because the quiescent current is such that a pulse never causes a zero crossing. And, depending on the quiescent current, the height of the pulse at which zero crossing occurs, if it does occur, will not be consistent between pixels, meaning that a single exposure, taken with one threshold, will not obtain accurately comparable counts between one pixel and another. This reduces the energy-resolving power of a photon counting system.

Medipix, as do other photon counting chips, provides an equalisation DAC for each threshold detector in each pixel. The DAC generates a programmable amount of current to adjust the quiescent state of the input signal at the threshold detector. It works by adjusting the signal level positively or negatively. The net effect is that all threshold detectors trigger at the same level (within the resolution of the equalisation DAC) for a charge pulse of the same size.

8.2 Using noise to measure pixel threshold deviations

Every amplifier is subject to the presence of noise that is inherent in its physical components. For example, resistors generate noise whenever current flows through them; this is known as series noise. Medipix pixel front ends are exposed to noise, and this sets a lower limit to the detectable size of charge pulses. Within the Medipix Collaboration, it is usual to make the assumption that all pixels in a Medipix chip have the same intensity of front end noise. Working on this assumption, front end noise is then used as a reference for testing the threshold detectors. Setting the `Threshold0` DAC to all of its possible values, in coordination with `ThresholdN`, `Dac_pixel` and the pixel equalisation DACs, the equalisation DAC value that brings each pixel as close as possible to a consistent zero-crossing level is established.

8.2.1 Noise zone consistency

The assumption that front end noise is a consistent reference may be questioned after seeing the observations in Figure 8.1. The graph shows the distribution of the width in `Threshold0` units of the noisy region for each pixel in the Hex CdTe camera. The chips show wide variations in the width of this noise zone. Chip C2 appears to be the closest to ideal, showing a relatively small range of variation in the noisy zone widths. Chip C1 shows very poor consistency. The variation between chips is high.

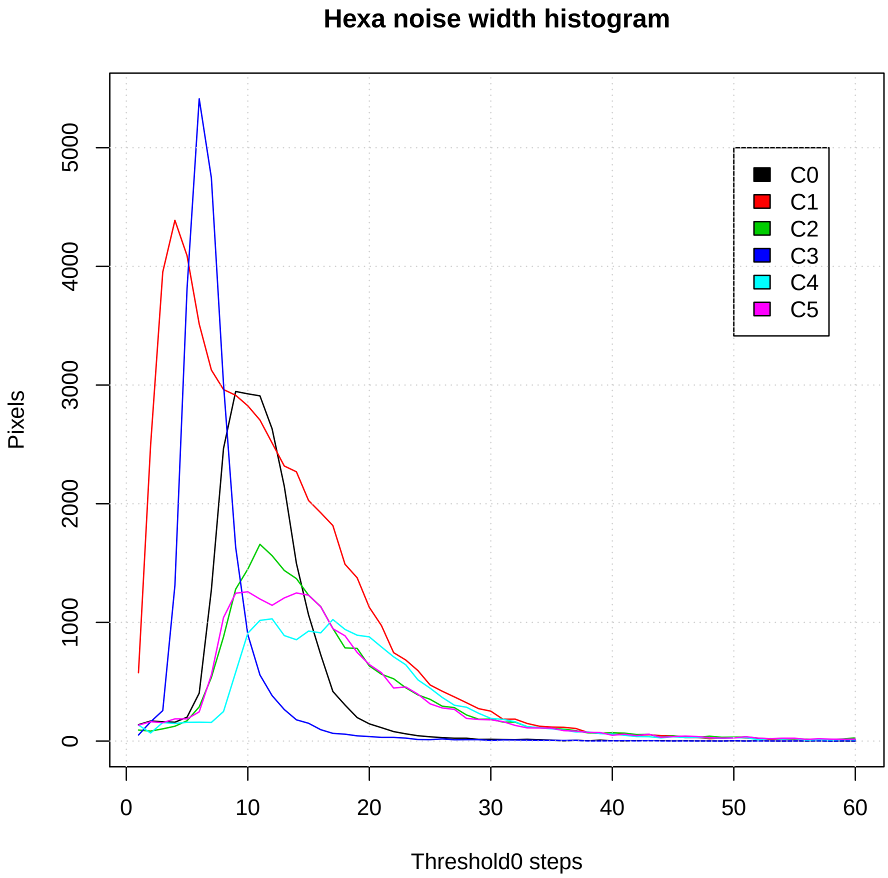

Figure 8.1: Distribution of Medipix3 front end noise “pulse” width

8.2.2 Inter-chip interference in the noise zone

An anomaly in Medipix3 behaviour when pixels are “in the noise” can be seen by comparing Figures 8.2 and 8.3. The graphs plot the number of pixels after an exposure which have reached the overflow count, 4095, versus the value of `Threshold0`. Each of the chips had been equalised and loaded with the appropriate equalisation file (*eqmap4*).

The first graph shows the distribution of the number of high-counting pixels in the six equalised chips when their threshold was scanned separately. The chips not being scanned have their thresholds set well above the noise zone. The second graph shows the same number, but while all chips are in the noise as they are scanned in a group. There is an offset in the threshold axis, and the area under the curve is reduced.

It appears that high count rates that occur when noise pulses are detected cause an increase in the chip power requirements. This would be expected to cause side-effects in one or more chip DACs. Such side-effects could alter the threshold detector switching point as well as other important bias levels. Supporting evidence for this suggestion was seen when I monitored the power supplies with an oscilloscope: a high frequency oscillation, of the order of several thousand hertz, was seen, and the average voltage level dropped by around 10 %.

8.3 Conclusion

The Hex CdTe camera was used to make observations of the front end noise behaviour during threshold scans in a set of six Medipix3 chips. Two significant phenomena were seen.

Firstly, the consistency of front end noise as a reference for threshold equalisation was poor. This inconsistency occurs within the pixels of most of the chips. It also occurs between chips.

Secondly, there was significant cross talk between the chips when they were all operating at a threshold at which high count rates were occurring. This kind of interaction may cause significant image distortion when photon flux is high.

Further work needs to be done. The test should be repeated with other multichip cameras, such as the silicon quads. For reasons not currently understood, the Hex CdTe chips performed quite a lot worse than the quad silicon assemblies.

Improved power supply stabilisation on the chip carrier, as close as possible to the Medipix3 chips is being implemented in a new architecture for the chip carrier.

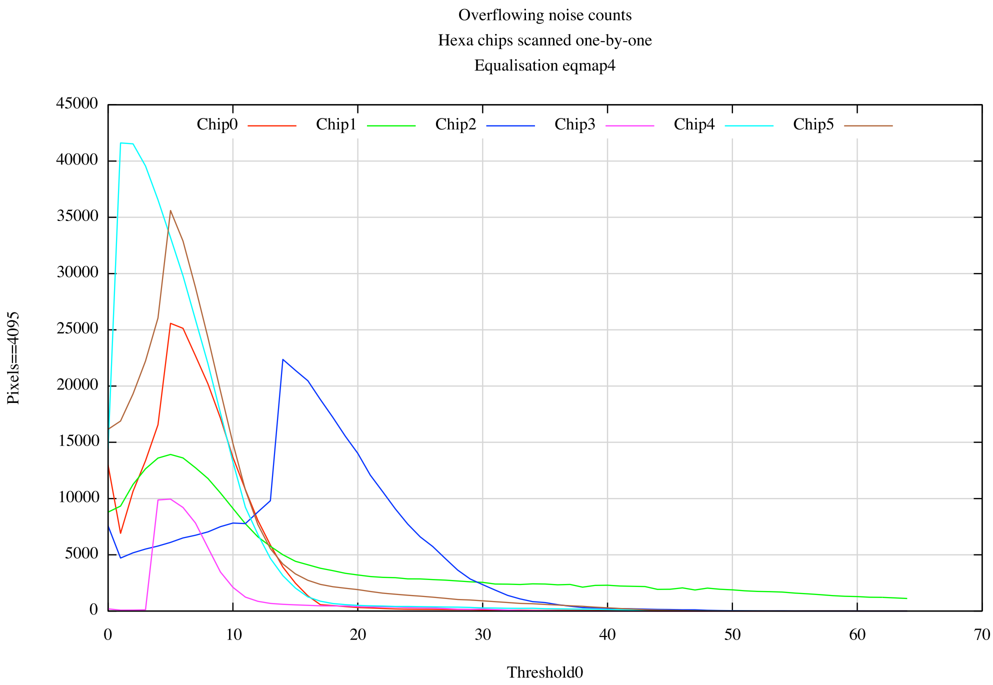

Figure 8.2: High counting pixels in equalised Medipix3 chips when only one chip is “in the noise” at time of scan.

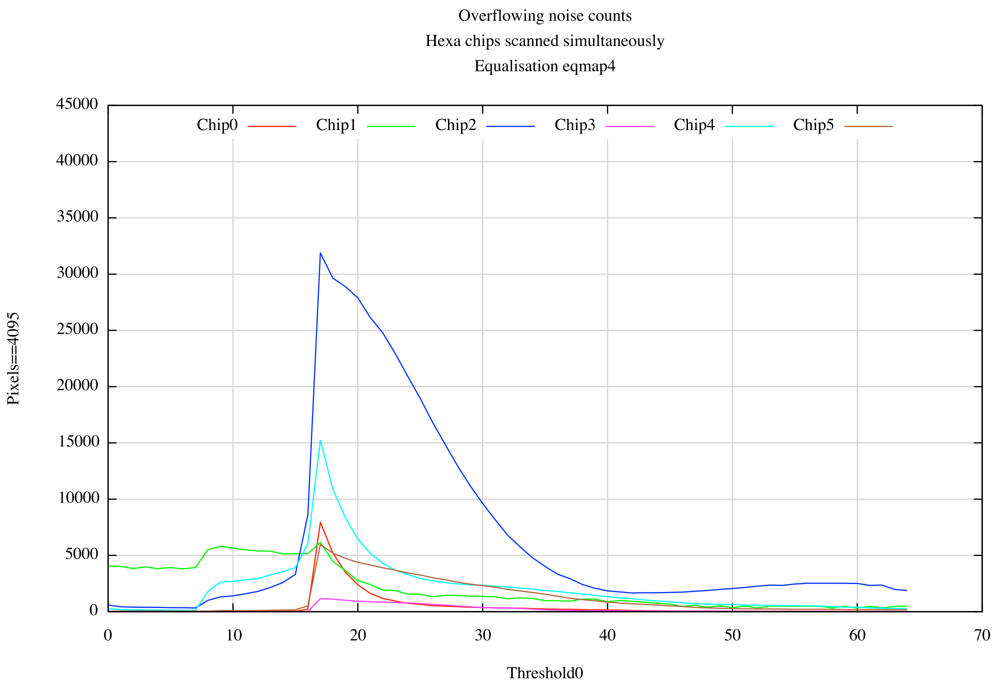

Figure 8.3: High counting pixels in equalised Medipix3 chips when all chips are “in the noise” at time of scan.

Chapter 9

Medipix3 charge summing mode

Contents

An attractive feature of Medipix that was introduced from the second version is the small pixel size, 55 μm on a side. Medipix1 had 170 μm pixels, and one motivation for trying smaller pixels was to explore the potential of a sensor with spatial resolution comparable to mammographic imaging media. The chip designers were aware of a significant disadvantage of such relatively small pixels: the loss of spectral accuracy due to two phenomena. Charge sharing, which happens when the charge cloud from a single photon interaction is split among neighbouring pixels, is naturally more likely when the pixel dimensions become comparable to the dimensions of the cloud. Fluorescence, a consequence of photoelectric ejection of inner shell electrons, causes "escape peaks" in the energy spectrum when the fluorescence photon has a mean free path of similar dimensions to the pixel. The photon has an increased probability of crossing the pixel boundary and being absorbed in a neighbouring pixel. Its energy is subtracted from the original impinging x-ray photon energy, causing a shift downwards from the true value. This shows up as a false peak, the escape peak.

Medipix3 includes a charge summing mechanism in each pixel based on "pixel communication", a sophisticated parallel computing system based on neural network logical elements. This mechanism, also known as "winner take all", reconstructs the original photon energy information from fragmentary charge sharing and fluorescence charge pulses. This has the effect of combining several false low-energy photon pulses into one high energy photon pulse. It attributes the reinstated pulse to the most likely pixel location, based on the pixel that received the largest fragment of charge.

Without charge summing, pulse fragmentation leads to errors in measurement of the energy and flux of photons. The effect is brightening in the low energy end of a set of images, and dimming in the higher energy zone.

False multiple-pixel hit reports serve to blur the image. One photon is attributed to several pixels and the benefit of the short wavelength of x-rays, with their minimal diffraction, is diluted. The spatial resolution of the system is degraded.

How can we test the charge summing function? The restoration of a single event from multiple simultaneous events in neighbouring pixels could be checked if we had a way of causing such simultaneous events. Several methods come to mind, but a simple method is to exploit the clusters of "hits" from energetic alpha particles on the Medipix sensor. A ready source of suitable radiation is the small fleck of radioisotope in an ionising smoke detector, a microcurie ^{241}Am source.

Alpha particles from ^{241}Am have more than 5 MeV of initial kinetic energy. This is reduced to zero in around 50 mm of air. If the source is close enough, alpha particles cause multiple simultaneous hits in a cluster of pixels when they impact on a the Medipix sensor layer. If charge summing mode is operational, a cluster of pixels will be combined into one single pixel. The first of the following two experiments is a test of this proposition.

The second experiment measures the energy spectrum of gamma rays from a relatively intense ^{241}Am source, using a cadmium telluride sensor with the Medipix3 ASIC. ^{241}Am emits gamma rays (photons) as well as alpha particles. The most common gamma rays from ^{241}Am, about one third of the total, have an energy of approximately 59.5 keV. Almost all of these will be stopped by 1 mm of cadmium telluride. Fluorescence from the sensor elements will occur, and the effects of this will be seen as escape and fluorescence peaks in the energy spectrum of ^{241}Am. Without charge summing, the energy spectrum of ^{241}Am will fail to show a very strong photopeak, and will show a tail of low energy photon counts. There will also be escape peaks of 36.8 and 32.6 keV from cadmium and tellurium respectively towards the low end of the energy spectrum. ^{241}Am emits some photons with an energy of 26 keV, and a peak at this point may also be visible in the spectrum.

9.1 Alpha particle cluster test

A Medipix3 with 300 μm silicon sensor, fitted to a CERN chip carrier, was clamped vertically in a retort stand (figure 9.1). The chip carrier was connected by a flat SCSI cable to a transition board plugged into a MARS camera motherboard.

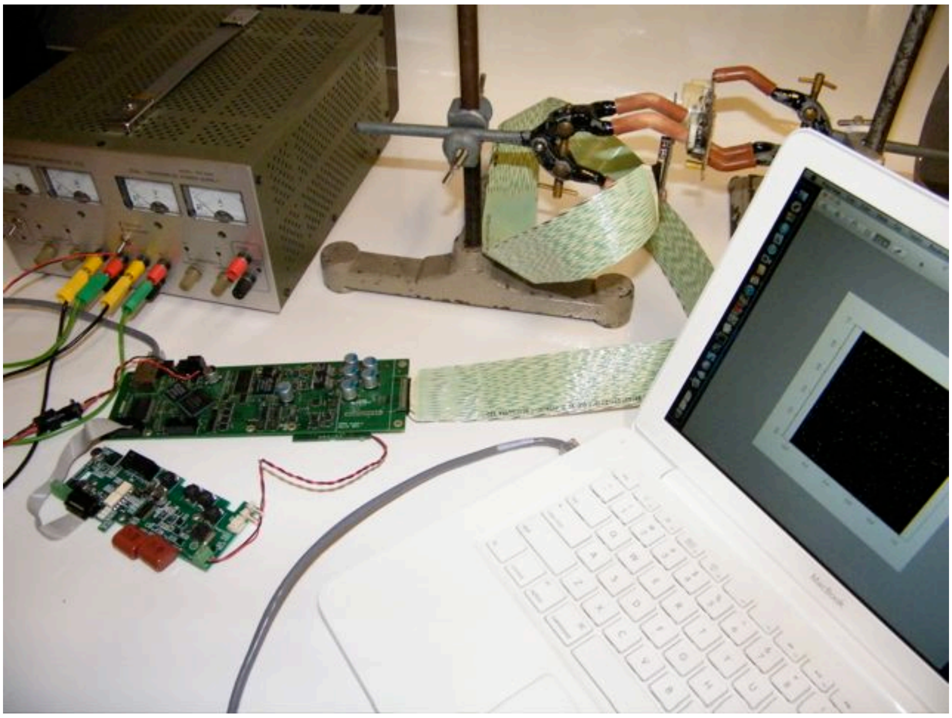

Figure 9.1: Alpha particle test setup. A bench power supply provides 12 V DC to the camera motherboard. A flat SCSI cable (pale green and white) connects the Medipix3 (CERN chip carrier) to the motherboard via a transition board. A high voltage board supplies bias via the red and black twisted wire to the transition board and through the SCSI cable. The high voltage board receives power and RS232 commands via the grey ribbon cable from the motherboard. The computer is connected with an Ethernet cable to the motherboard.

The high voltage leads of the transition board were connected to a MARS camera high voltage board which received power and commands via cables connected to the motherboard.

The smoke detector, which was attached to its original circuit board, was clamped in a second retort stand and placed close to the Medipix3 chip (figure 9.2). There was no material, other than the foil cover and air, between the ^{241}Am source and the Medipix sensor.

The 12 volt power supply was connected to the camera, and a desktop computer was connected by Ethernet. The DACs were set to the values in table 9.1, with other specifications as follows: `Exposure` 1000 ms, `Threshold0` from 256 to 510 in steps of 2, `Polarity` 1, `Gain` 0, `CSM` 1, `Repeat` 32, `HV` 100 (`Peltier` not attached) and a set of images taken and saved to disk. The procedure is repeated with charge summing mode turned on.

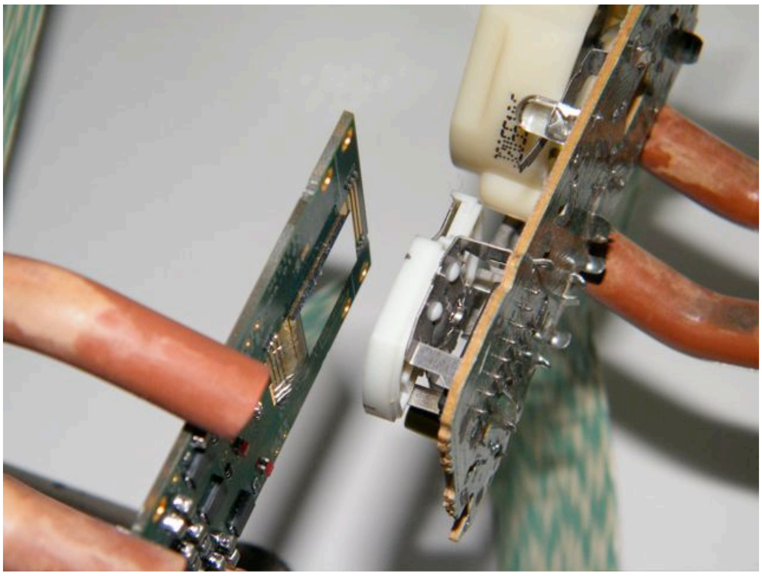

Figure 9.2: The Medipix3 chip is on the left and faces the alpha particle source in the smoke detector. The source is protected by a white surround.

The clusters of pixels where alpha particles have hit have been analysed by a "connected components" algorithm. The algorithm labels all pixels that touch each other on a side or a corner with the same cluster number. The number of clusters at each threshold, when charge summing mode is disabled, is graphed alongside the number of single pixel hits, when charge summing mode is enabled, in figure 9.3.

The graph shows that the cluster count when charge summing is disabled is consistently 5 to 10 % lower than when charge summing mode is enabled. Possible explanations for the difference are given in section 9.3.

9.2 ^{241}Am gamma ray spectrum

When Thomas Koenig visited our lab in February 2012, he was interested in comparing the results of charge summing mode between Medipix2 and Medipix3 ASCICs fitted with CdTe sensors. He has extensive experience with CdTe on Medipix2 chips. His observations showed that, with 55 μm pixels, the Medipix2 can not resolve meaningful spectral information from ^{241}Am 59.5 keV gamma rays. I was able to help Thomas make some of the first such observations with a Medipix3 in charge summing mode.

Our Hex MARS camera, that is, a six-chip Medipix3 with cadmium telluride as sensor layer, was used. A 1.66 GBq (as of 1974) ^{241}Am source was made available at the Medical Physics department of Christchurch Hospital. The ^{241}Am

Table 9.1: Medipix3 DAC and other settings for alpha particle test of charge summing mode.

DAC	Value
Threshold0	see text
Threshold1..7	511
Preamp	120
Ikrum	20
Shaper	200
Disc	255
Disc_LS	200
ThresholdN	32
DAC_pixel	120
Delay	128
TP_Buffer_In	127
TP_Buffer_Out	127
RPZ	127
GND	127
TP_REF	127
FBK	163
Cas	ExtDAC=1000 mV
TP_REFA	255
TP_REFB	255
Equalisation DACs	0

is housed in a small brass container with an exit aperture that produces a narrow beam of particles and photons. The source was fastened in a retort stand, placed about 5 mm from the protective cover on the camera aperture, and directed towards the centre of one of the six Medipix3 chips (chip number 0, the first physical chip). This chip is known to have the best quality and size of its sensitive area, although it has a corner and some spots that are insensitive to radiation due to missing bump bonds (and other issues).

The camera was connected to a computer by Ethernet, and a 12 V power supply was provided. The basic Medipix DAC settings are listed in table 9.1, with additional specifications as follows: `Exposure` 3000 ms, `Threshold0` from 511 to 1 in steps of 3, `Polarity` 0, `Gain` 1, `CSM` 1, `Repeat` 40, `HV` 400, `Peltier` 1000 mV.

Before the observations were taken, the camera was powered on for about an hour to allow the sensor bias voltage and leakage current to stabilise. This precaution is based on past experience with the use of CdTe for a series of observations

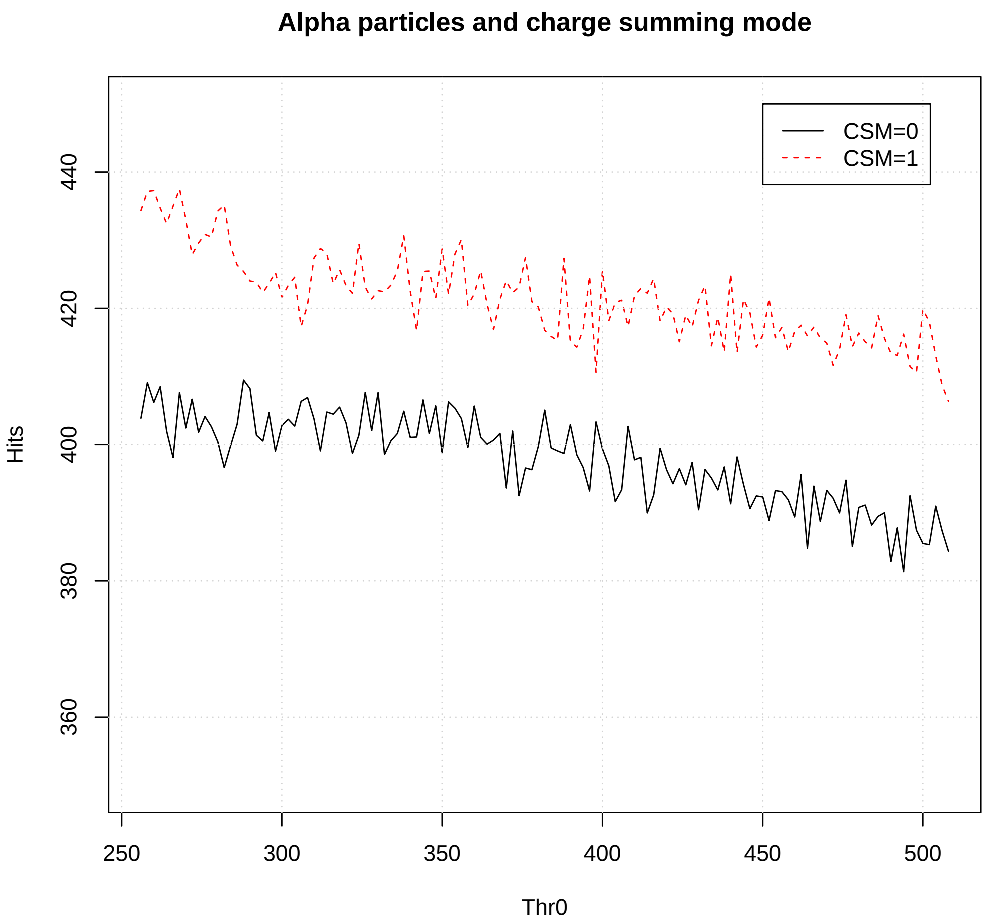

Figure 9.3: Alpha particle hit count with and without charge summing mode for a silicon Medipix3.

over long time intervals (Koenig, 2012; Aamir et al., 2011b).

Many pixels showed distorted count profiles, probably because the chip had not been equalised. After filtering out distorted results, about 6000 pixels with valid spectral responses were available. Their spatial distributions, with colour coding to indicate the total number of counts at the lowest valid threshold, are shown in figure 9.4. There is a significant insensitive area in the upper left corner of the image; this is believed to be caused by a progressive failure of bump bonds.

Using the same ranges of total counts, the differential rate of counts versus threshold are shown in figure 9.5.

9.3 Discussion

ALPHA PARTICLES The alpha particle experiment demonstrates that charge summing combines multiple hits into single pixels. Charge summing shows a total of 5 to 10 % more hits at each threshold. One explanation could be that, because summing takes place, there are events being reconstructed from several neighbouring pixel interactions each of which is not high enough to reach the threshold during single pixel operation.

GAMMA PHOTON SPECTRUM Charge summing has not had the expected effect, of producing a clear spectrum without a tail of low energy counts. Not only is there a tail towards the lower end of the energy range, but the count rate is relatively larger for pixels receiving a greater number of hits. This effect may be due to the chip not being equalised, which almost certainly disrupts the charge summing algorithm. Polarisation of the cadmium telluride sensor material may also be a factor in the count rate dependency.

On the positive side, a Medipix3 chip without equalisation has resolved spectral features in the gamma photons from ^{241}Am at a spatial resolution of 55 μm. Unlike its Medipix2 predecessor, it can recover information from the coincidence of split charge clouds in neighbouring pixels.

9.4 Conclusion

The MARS camera development, for Medipix3 in particular, has provided us with an early opportunity to explore the novel new feature of pixel communication and charge summing. Problems have been known to exist in the design and manufacture of the first version of Medipix3. In spite of these problems, there is promise of a new spectroscopic capability in this sophisticated chip design.

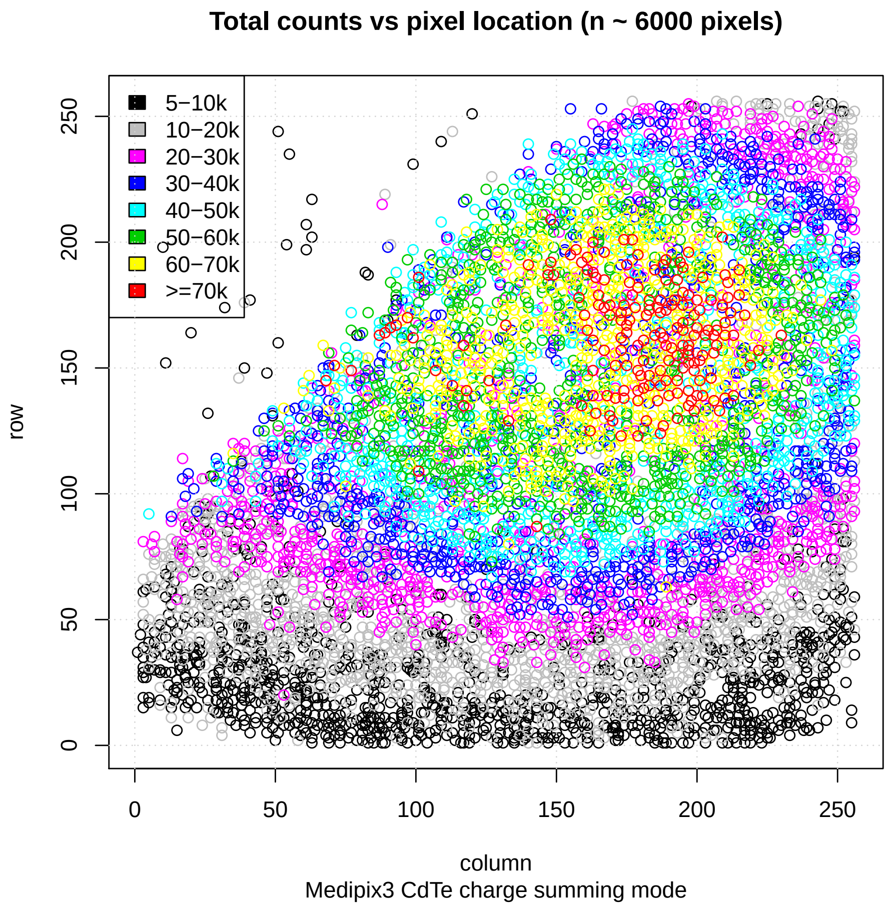

Figure 9.4: ^{241}Am pixel counts, coded by range of total counts. There is an insensitive area in the upper left corner. Comparing Figure 10.1 (bottom left chip), taken in mid 2011, to this graph from a measurement in early 2012, the insensitive area has grown in size.

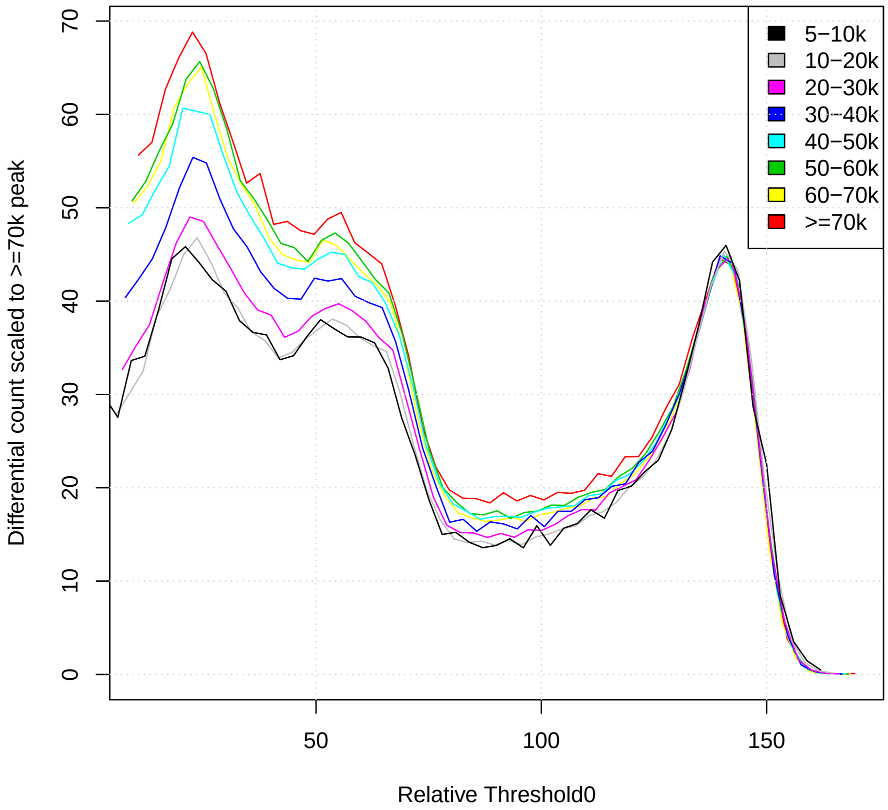

Figure 9.5: ^{241}Am counts versus threshold, broken down by total count range.

Chapter 10

Conclusion

This thesis has presented an overview of the physical components and the software systems that make up the MARS camera. The detailed descriptions - design drawings, electronic schematics and source code - are not to be found here. My contribution has been to "integrate" a diverse set of concrete hardware and abstract software ideas, most of which originated from other workers, into the working camera, and to perform some characterisation of new Medipix3 features.

What is "integration"? My definition, informal as it is, is *the joining together of things that are intended to fit together, to work together, to communicate, but for which the interfaces have not been perfected and do not work; hence, understanding of both (or several) sides is needed, tools and techniques are understood and applied with skill in diverse areas and operating environments; open-ended problem solving, diagnosis and adaptations are called for, and are provided in a productive, robust and reliable way.*

The outcome of my work is a working MARS camera: a fast, usable, flexible, reliable spectral x-ray imaging device that works, with single chips, and multichip tiled arrays, of Medipix2 and Medipix3, in the MARS CT scanner. I, and others in New Zealand and overseas, have used the camera for novel spectral CT imaging. Interesting new results are being obtained week by week. There are good reasons to expect a leap in spectral image quality in the near future, when the redesigned version 3.2 of Medipix3 with sensor layers becomes available, and the required camera adaptations are made.

I worked to integrate several operating environments. In respect of the electronic hardware and FPGA, my involvement was limited: I have become quite familiar with the schematics and block diagrams; I have learnt where to find the signals that need to be checked; and I have found ways of measuring signals in the most difficult context I have worked, due to fine track sizes, wire bonds of the order of 20 μm in size, and other issues. I found several faults in the hardware: some design faults, and some manufacturing faults. For example, connections that had not been made. Another example: a precision resistor that was left out and covertly caused Ethernet to fail on the new revision C boards. For the FPGA I was able to ask Marcus (ILR) for a couple of small changes: the removal of an inverter, and the alteration of the direction of a shift register.

I took over responsibility for the camera firmware in June 2010. Until that time I concentrated on making the camera work, handing off any firmware problems to Marcus, the initial author. Occasionally I would request specific changes. This can not have been easy for him, not least because the software development kit (SDK) has a few quirks that induce distortions in basic things like file names, and in directory heirarchy. Eventually I began to take over the design and maintenance of the camera subset of the PC library. Originally developed by Dave van Leeuwen and Jethro Donaldson, the library also supports scanner stepping motors and x-ray tube, and cabinet switches, display and interlocks. Mike Walsh had picked up responsibility for the library, but for the camera subset this was not very practical.

During the latter part of 2009, while Dave van Leeuwen was translating the Python prototype to C for the library, I contributed some code to supplement his work. For example, I designed the functions to access the Medipix3 registers. As another example, I supplied code to serialise and deserialise the Medipix2 counter matrix. At year's end, Jethro Donaldson returned as a summer student and made significant changes to the library organisation. At the time that I began to take greater responsibility for the camera subset of the library, Mike was the maintainer. I made substantial changes to key parts of the library in order to improve readout speed, and to deal with the complications resulting from several permutations in the assembly of Medipix3 chips onto chip carriers.

The significant MARS camera projects that I've worked on are:

- Track down and arrange solutions for firmware and hardware problems in the prototype hardware. Take the first images using the complete camera to PC chain, using a Medipix2 MXR as substitute for the late-to-arrive Medipix3. I achieved this milestone a few days before taking the prototype system to Europe, in May 2009, to demonstrate at the regularly scheduled Medipix collaboration meeting in Grenoble, France, and at IEAP in Prague.

- Perform trials with the first Medipix3 to be released to us by CERN, a chip without sensor layer but (in principle) in working order. The purpose of these trials was to give confidence that the basic design of the camera prototype was sound. The outcome was that undocumented problems were seen and reported by me, then confirmed by Winnie Wong at CERN. The design of the camera prototype was proven to be sound.

- Take over the Medipix2 code, and Medipix3 code developed by Marcus Clyne (ILR) in close collaboration with Rafa Ballabriga (CERN, main designer of Medipix3). I did this in June 2010, and had to deal immediately with complications associated with multi-chip support, and with inconsistent Ethernet startup.

- Implement multiple chip support, first for the "Quad" Medipix3 (completed a couple of weeks after the Darfield quake in September 2010), and late in the year for the dual CdTe Medipix2 MXR.

- Improve the rate at which images are read out of the camera by simplifying the low level protocol that was used for bulk data transfer. I replaced the "ping-pong" method of polled data transfer with an un-checked streaming transfer which runs close to the achievable speed of a single 32-bit shift register and Gigabit Ethernet (but which is vulnerable to packet loss when the PC can't keep up). During this development, which was completed shortly after the destructive 22 February quake in 2011, I trialled readout with parallel "interleaved" shift register operation. This work showed that further speed improvements were feasible, but I shelved it due to ongoing structural complications in multi-chip handling, both in the camera and PC.

- Investigate and help to solve the problem of providing reliable high voltage bias to the dual CdTe MXR (due to the higher voltage required by CdTe). Problems were found in voltage range, stability and current supply. These led to a major redesign of the high voltage board. The board also had a Peltier driver and control system added, and the impact of these changes took many months to settle.

- Obtain images with a hex CdTe Medipix3 camera. I studied the equalisation process, which led me into statistical challenges, dealing with 64k independent random noise sources, with pulse analysis on Medipix3. Eventually I obtained images, but they were compromised by problems with most of the six Medipix3 chips. Four of the chips did not function normally, and the bump bonding for all of them was in a poor state (Figure 10.1).

- Visitors from the Mayo Clinic and Virgina Tech were expected in September 2011 and the improvement of image transfer speed was made a priority. I reinstated the experimental parallel interleaved shift register functions, and obtained a significant speed improvement for multi-chip Medipix3 cameras, as well as for the dual CdTe MXR. A complete set of CT projections was made of a live mouse, the time taken being less than twenty minutes. The VT visitors were able to take some valuable data back with them, and a significant article has been published that includes images derived from that data.

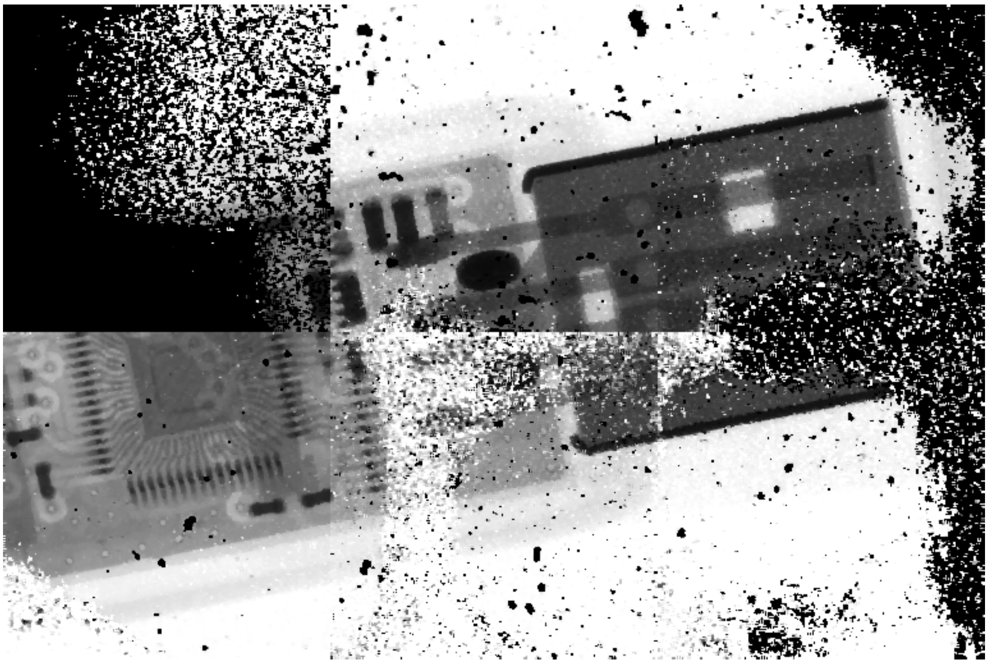

Figure 10.1: Image of USB flash drive taken with hex CdTe chip carrier fitted to MARS Camera. Many bump bonds appear to have failed.

- Problems with operation of the second counter of Medipix3, and the use of 24-bit mode, showed up during my study of the equalisation process. I found that the problems were caused by long-standing flaws in the Medipix3 v3.0 counter reset workarounds, and was able to implement a solution, leading to a more robust and accurate system.
- As the pressure to improve camera performance fell off, I was able (in December 2011) to do some exploratory work with charge summing mode, using alpha particles from a low intensity radio-isotope (the americium 241 in an ionising-type smoke detector). The work has not yet reached a conclusion, but - if and when it resumes - it will probably be with a completely new version of Medipix3, version 3.2.
- During the visit of Thomas Koenig from Germany, I had the opportunity to resume investigation of charge summing mode in February and March of 2012. Thomas and I shared the data gathering work, and I went on to perform all of the data analysis.

The scientific outcomes of my work, which are reported in a number of publications of which I was a co-author, are listed at the end of chapter 1, the Introduction. Appended to that list are references to several papers that acknowledge the use of the MARS CT scanner, which includes the MARS camera, and are thus derived from my work.

In the time since this thesis was submitted, the latest design and manufacturing run of Medipix3 version 3.2, also known as the “RX”, has become available to the MARS group. Preliminary testing has been done by the author and is ongoing by other members of the team. Several significant “RX” features remain to be tested. Some of this work will be done using a new camera architecture in the next generation of the MARS CT system being readied for commercial release. Real improvements, beyond a valuable step up in quality already seen in Medipix3 v3.1 (Figure 10.2), are observed in the consistency of pixel to pixel electronic circuit performance. Reports from the CERN group and Medipix3 Collaboration members also show promising performance of the “RX” in charge summing mode.

There are complex trade-offs in photon counting imaging detector design. Materials scientists are being asked to develop semiconductors with a good combination of stopping power and physical stability for the sensor layer. There is a tension in the design of Medipix3, related to the physical properties of the sensor material, between pixel size, charge sharing correction by inter-pixel communication, accurate per-pixel count rate, and the number of counter channels. There needs to be further work to find the best pixel size for x-ray imaging applications with the Medipix architecture. Sensor materials need to be improved, especially the CdTe compounds with their high density and stopping power but hard to control homogeneity and dimensional stability. While these are ongoing research problems, it is clear that “RX” has exciting features ready to be explored.

The results we are seeing in quantitative spectral CT in the MARS group provide strong evidence that Spectral CT will make a real contribution to pre-clinical radiology. It is becoming clear that Spectral CT is directly relevant to medicine and that its clinical applications should be pursued with urgency.

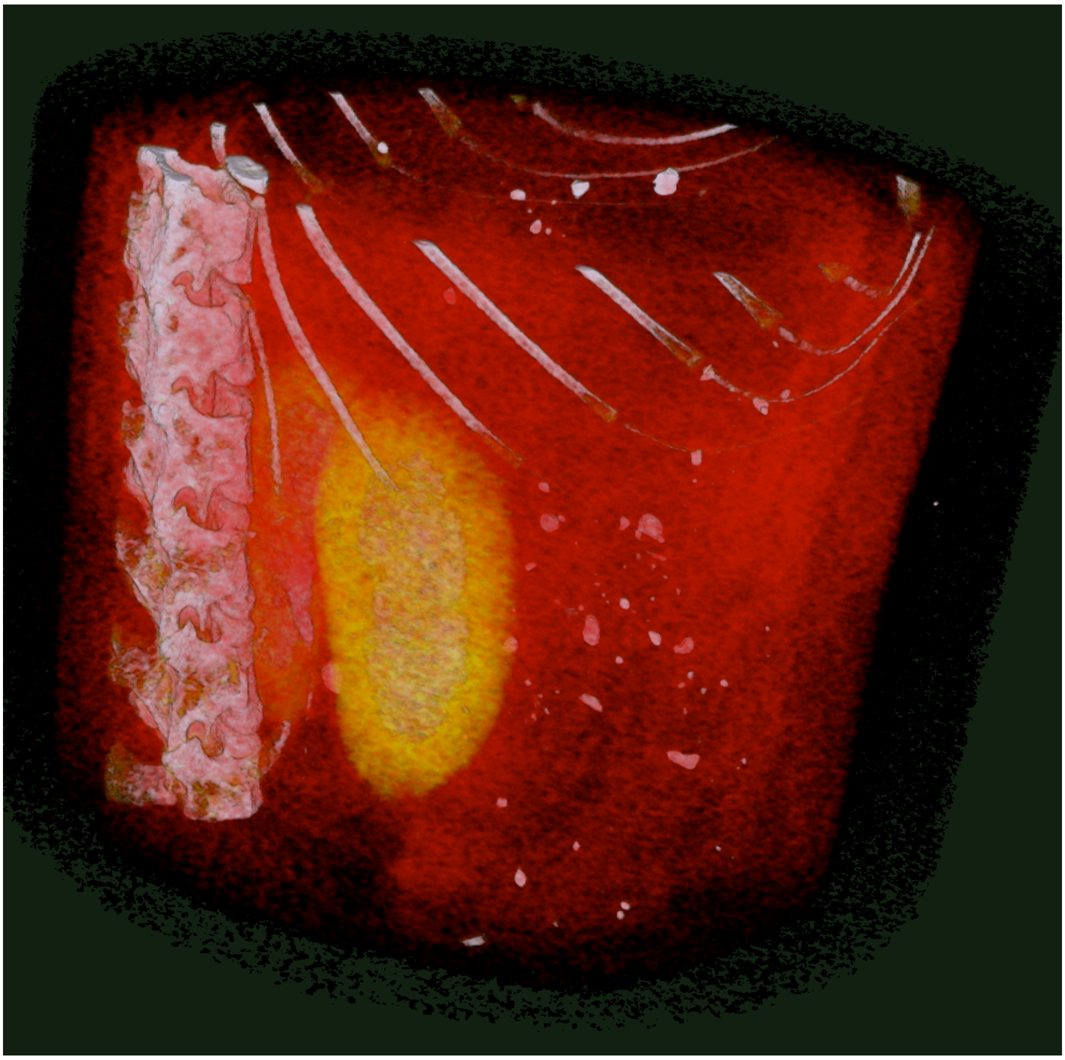

Figure 10.2: Three dimensional x-ray CT image of section of thorax and abdomen of a mouse, showing the outline of its kidneys highlighted by gold nanoparticles. The outer cortex and inner medulla of the kidney can be distinguished. Part of the vertebral column, ribs, and unidentified radio-opaque digestive system contents are also visible. A quad chip carrier containing Medipix3 v3.1 chips with a silicon detector layer was used. The colours in this image were applied manually. (unpublished)

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