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Highly Miniaturised Radiation Monitor (HMRM) Status Report

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HMRM programme aim

Aim of phase A/B: Develop a “chip sized” prototype radiation monitor suitable for application in:

  - Coarse radiation housekeeping
  - Alert and saving function
  - Support to platform and payload systems

- The monitor should address a number of key requirements
- The monitor should have additional option of particle spectrum reconstruction

HMRM consortium

Consortium Member	Role
STFC - RAL Space	• HMRM Consortium Lead • Overall design and development of HMRM • HMRM tests
STFC – Technology Department	• HMRM ASIC Sensor Design and Development
Imperial College London – High Energy Physics	• HMRM Particle radiation simulation • HMRM Particle Identification algorithm development • HMRM initial tests
ESA ESTEC	• Technical contract management

Sensor Tradeoff

• Key tradeoff in the architecture of the sensing element of the HMRM was between a Silicon Diode and Active Pixel Sensors

• APS sensors have several advantages for application in the HMRM

Parameter	Comments
Mass	Integrating the detector function with the signal readout makes APS much more compact
Sensor integration	The sensing element is fully integrated on the monitor chip with APS sensors
Signal quality	Able to achieve 5-10 e^- rms with saturation of 19ke^- with APS
Power supply	Bias voltage of CMOS is 3.3 V and no need for “high” voltages to drive the diode into depletion
Flux dynamic range	The APS is able to be electronically shuttered to avoid pileup in high flux environment

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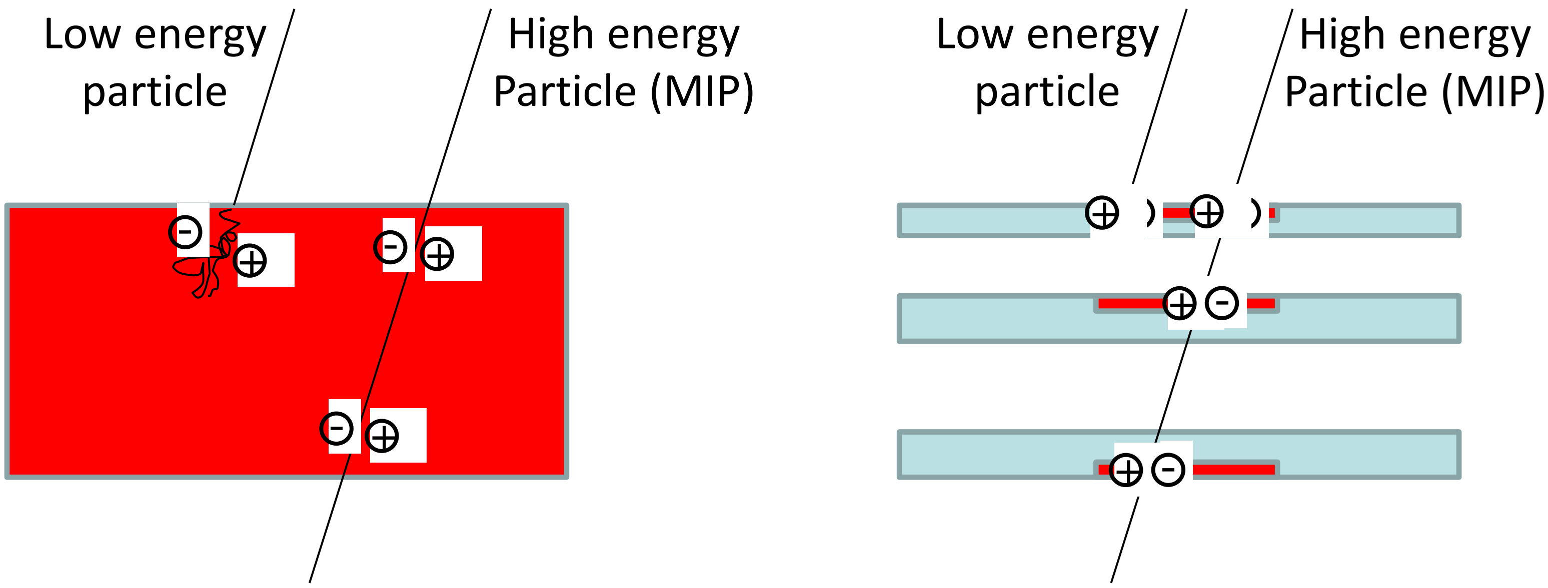
Sensor Tradeoff

Silicon Diode **Active Pixel Sensor**



- Ambiguity exists where the energy deposited in the detector by a low energy particle is the same as the energy deposited by a MIP passing through the detector.
- Active volume of Silicon diode: > 50 µm
- Active volume of APS detector: 12 µm with 50-500 µm substrate
- With APS sensors, careful selection of silicon substrate thickness allows the dE/dx curve to be sampled and uniquely identify the particle species and energy.

HMRM Initial Design Summary

Characteristic	Specification	
Sensing element	50 x 51 array of 20 µm x 20 µm , 4T CMOS APS detectors	
Configuration	Either single chip, or integrated monitor	
Mass	Integrated monitor: 52g (including fasteners and connector) in a stack configuration	Single Chip: 0.8 g
Power	1-2 W depending of number of detectors in stack and architecture of power supply	Single Chip: < 200 mW per ASIC (requirement)
Volume	Integrated monitor: 20x25x30mm - 15 cc	Single chip (unpackaged): 2.54x10x0.6 mm
Radiation measurements	Integrated Monitor: Dose Dose rate Particle radiation spectra: • Electrons: 0.06 – 6 MeV • Protons: 1 – 500 MeV	Single Chip: Dose Dose rate
Maximum flux	10^8 #/cm^2/s (TBC)	
Aux. measurement	Temperature	
Interface	Integrated Monitor: Data: TM/TC CCSDS CAN Power: 5 V (standard)	Single Chip: Data: CMOS logic I/O Power: 3.3 V + 0.3V references

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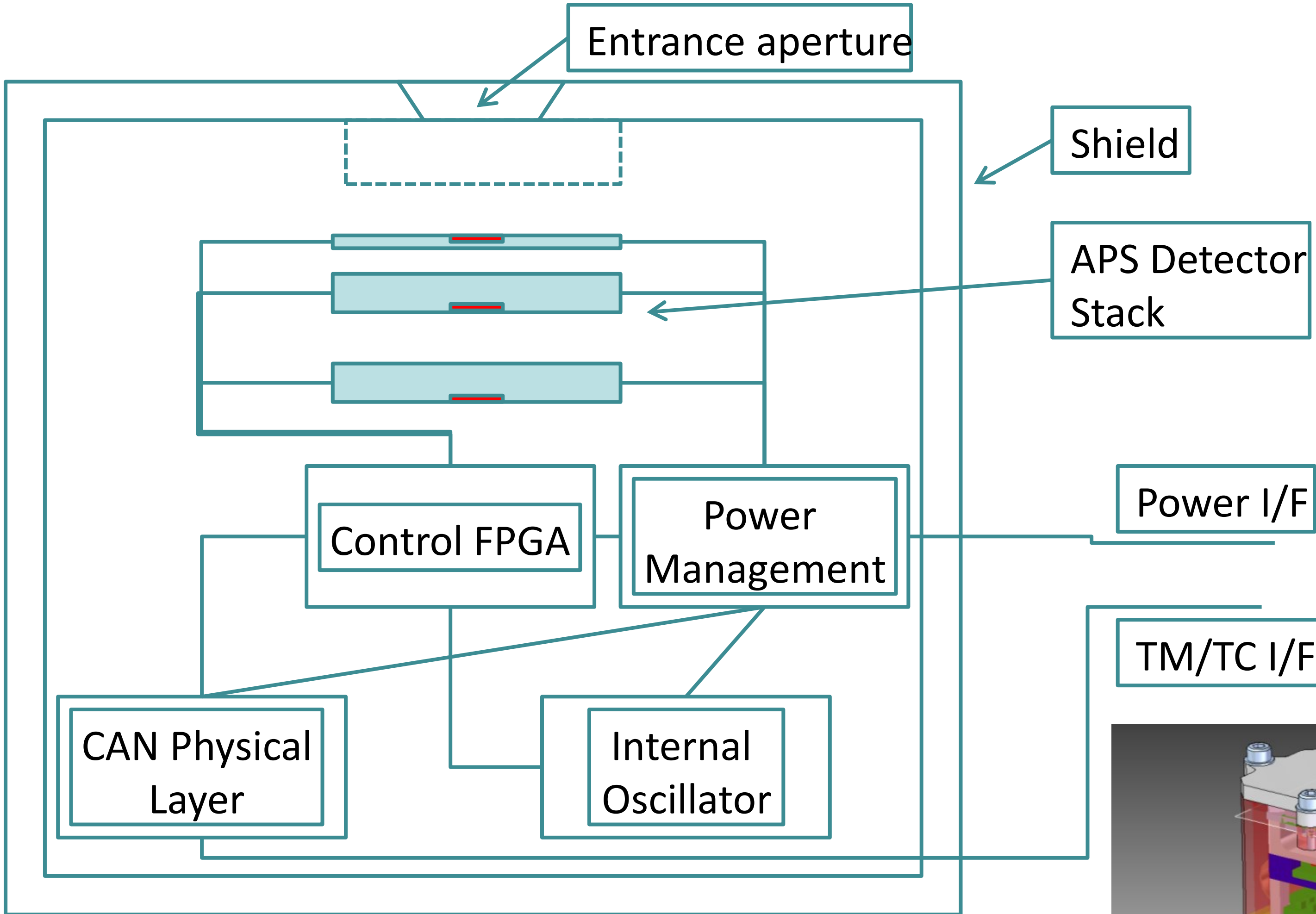
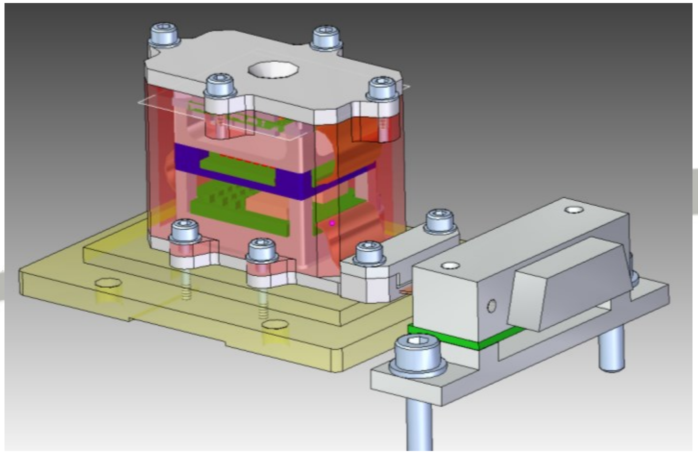
HMRM Block Diagram and CAD model





HMRM instrument programme status overview

- The HMRM instrument Phase A/B was close to completion in 2012 (the HMRM Final Presentation in May 2012).
- At the end of the phase A/B:
  - Design of the monitor prototype was complete with demonstration of the potential of applying CMOS APS technology to the design of a highly miniaturised spacecraft radiation monitor.
  - Geant4 modelling of the expected response have been conducted.
  - Science algorithm for the particle identification has been developed, as well as algorithms for particle counts, total dose and dose rate, these algorithms have been implemented in the FPGA.
  - The HMRM instrument was built and included into the payload of the UK TechDemoSat-1 satellite (2 sensor configuration). Was flown for 3 years 2014-2017.
  - The second generation of CMOS ASIC sensors has been fabricated.

HMRM instrument programme status overview

- In addition, since 2012:
  - The 2nd generation of the ASIC have been assembled in a stack configuration of 2 sensors, on the PCB and programmable FPGA.
  - This instrument prototype was extensively tested and calibrated, including Fe-55, Sr-90 tests and tests with the proton beam at PSI. Only digital readout has been used.
  - It was demonstrated that the instrument with 2 sensors at least can work as a particle counter.
  - The HMRM Status Presentation in November 2016.
- With additional funding from the STFC Innovations - Proof of Concept contract:
  - The 3rd generation of ASIC sensors has been developed in order to reduce power consumption.
    - The ADC offset compensation on the ASIC was redesigned.
    - Digital logic was simplified.

Aim of the recent work

The aim of the recent work was characterisation of the 3rd generation of the ASIC sensors:

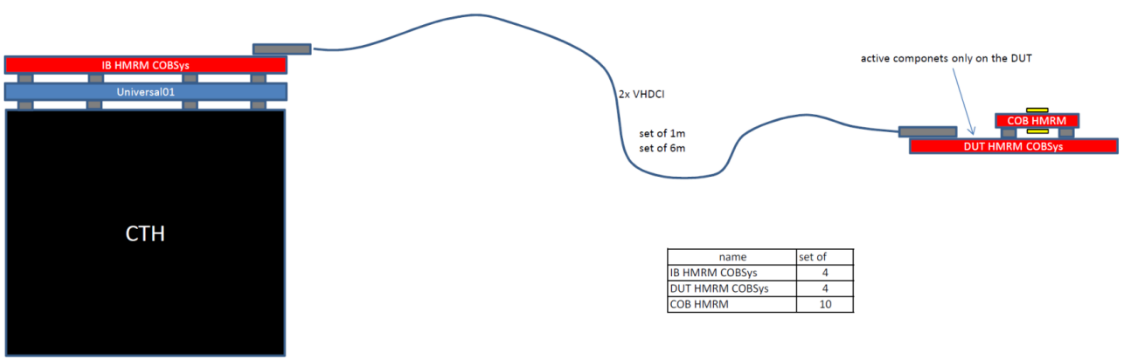
- Power consumption estimations.
- Characterisation of the sensor performance via analogue readout.
- Stability/consistency of the ASIC behaviour.

3rd generation of ASICs:

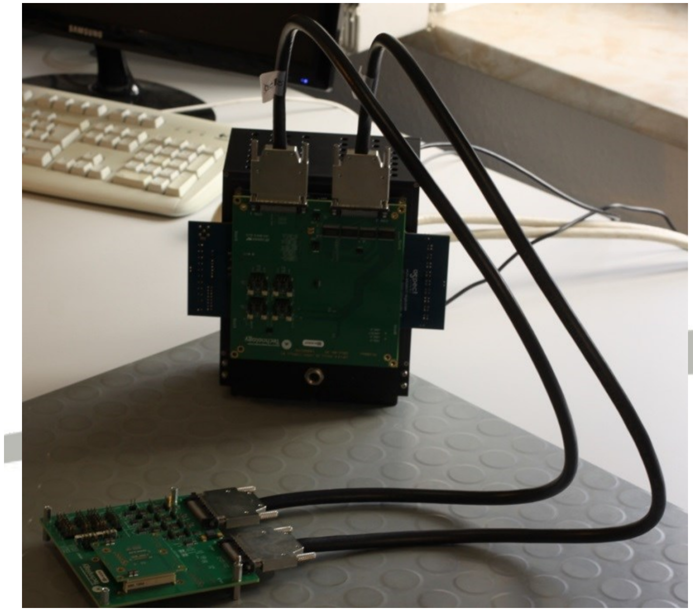
- ASIC is a standard 4T CMOS APS monolithic sensor. Many functionalities are already incorporated on the ASIC, such as ADC and threshold generator.
- HMRM ASIC core: a pixel array, 50 rows and 51 columns, each pixel is 20 μm by 20 μm, active area is 1 mm^2.
- Stack of 2 ASIC sensors on top of each other (back to back), one with thickness of 50 μm (top sensor) and the other of 250 μm (bottom sensor). Both sensors have epitaxial layer of 12 μm.
- Multiple detectors: high-resistivity and low-resistivity substrates. Expect less charge sharing in high-res substrates devices.
- 2 low-res devices (HMRM05, HMRM06) and 4 high-res devices (HMRM07-HMRM10) were tested with light and Fe-55 source, 2 low-res and 2 high-res devices were tested with the proton source.

Test system

- The test system was re-designed in order to use the aSpect Compact Test Head (CTH) instead of FPGA.
- The CTH camera allows transmission of two different readout modes: analogue and digital.
- New test system consists of the COB with 2 ASICs which connects to the device under tests (DUT), and DUT connects to the interface board (IB) of the CTH via 1 meter or 6 meter cables.



name	set of
IB HMRM COBSys	4
DUT HMRM COBSys	4
COB HMRM	10



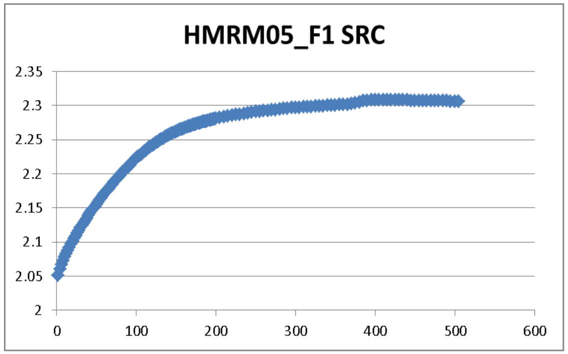
Test system

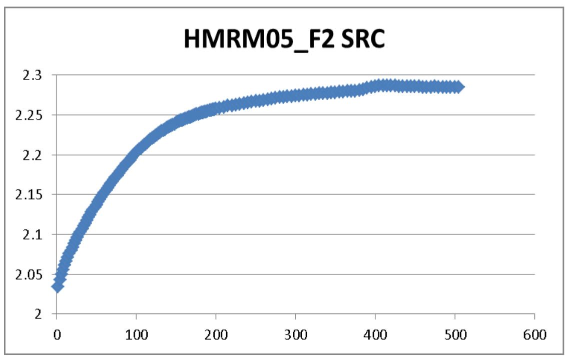
- Both readout modes were tested.
- Analogue readout allows to bypass the on-chip digitisation and read the actual value of each pixel, required for accurate detection of deposited energy, characterisation of ASIC performance and better analysis of charge spreading between the pixels. Rate is 100 fps.
- Digital readout: in each image a value from each pixel is a 3-bit value, obtained by comparing the pixel output after CDS with 7 pre-defined thresholds. All pixels are readout simultaneously. Rate 10,000 fps.
- The readout of each sensor is done from two halves (e.g., F1, F2, B1, B2). From each test, 1000 or 3000 images were collected for further analysis.

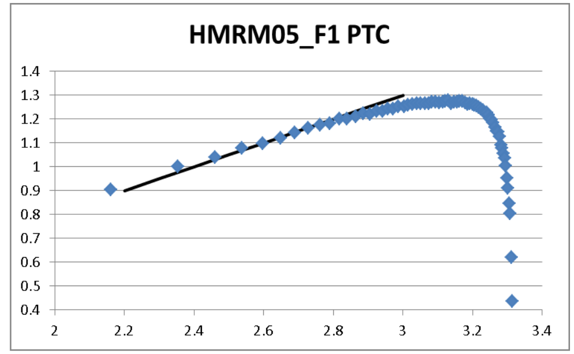
Sensor characterisation – analogue readout

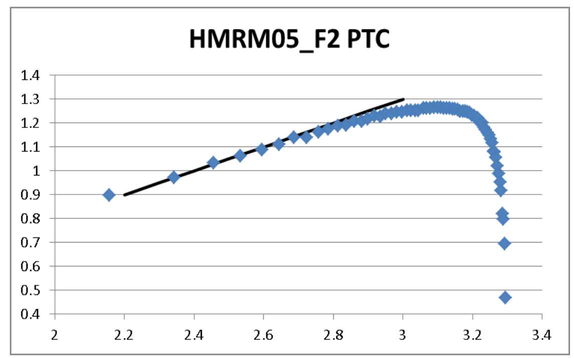
Example: Sensor response for different light intensity, analysis via PTC method.

Signal response curve:
X axis - light intensity in [nW/cm^2],
Y axis - output DC level in [V].









Photon transfer curve (log-log);
X axis - mean of signal in DN,
Y axis - standard deviation.

	Gain (µV/e)	Mean Noise (e)	Linear Full Well (e)	Max Full Well (e)
HMRM05_F_1	84.798	53.0	1689	3221
HMRM05_F_2	65.27	53.1	2088	4101
HMRM05_B_1	91.632	50.1	1752	3170
HMRM05_B_2	52.133	45.1	2645	5521

Sensor characterisation – analogue readout

Performance summary of the high-res HMRM07 – HMRM10 ASICs:

	Gain (µV/e)	Mean Noise	Linear Full Well	Max Full Well	Gain (µV/e)	Mean Noise , e-	Linear Full Well	Max Full Well
	Tests with 1 meter cable				Tests with 6 meter cable			
HMRM07_F_1	57.03	45.3	2348	4446	61.27	49.1	2168	4042
HMRM07_F_2	50.06	45.3	2571	4978	59.20	49.7	2056	4093
HMRM07_B_1	59.59	45.7	2425	4668	64.99	43.8	2203	4130
HMRM07_B_2	64.25	47.1	2316	4292	59.02	46.3	2254	4511
HMRM08_F_1	57.31	44.8	3878	6527	50.61	46.6	3010	5088
HMRM08_F_2	59.06	43.1	3797	6362	66.36	43.7	2079	3891
HMRM08_B_1	81.46	42.1	2777	4443	67.67	47.7	1874	3693
HMRM08_B_2	67.31	41.7	3293	5325	71.82	48.9	1706	3404
HMRM09_F_1	41.31	46.0	3096	5967	37.59	53.0	3475	6364
HMRM09_F_2	42.47	46.8	2895	5839	43.59	44.3	2781	5489
HMRM09_B_1	55.74	58.8	2681	4611	43.59	44.3	2781	5489
HMRM09_B_2	38.68	52.3	3393	6586	38.72	43.4	3686	6564
HMRM10_F_1	51.83	54.6	2797	4938	36.34	47.8	3607	6867
HMRM10_F_2	45.36	47.2	3135	5651	57.08	46.8	2328	4394
HMRM10_B_1	49.82	46.7	2969	5474	68.78	51.1	2163	3872
HMRM10_B_2	41.64	46.2	3621	6285	48.20	41.1	2672	5276
Average	53.9	47.1	3000	5400	54.7	46.7	2553	4823

Sensor characterisation – analogue readout

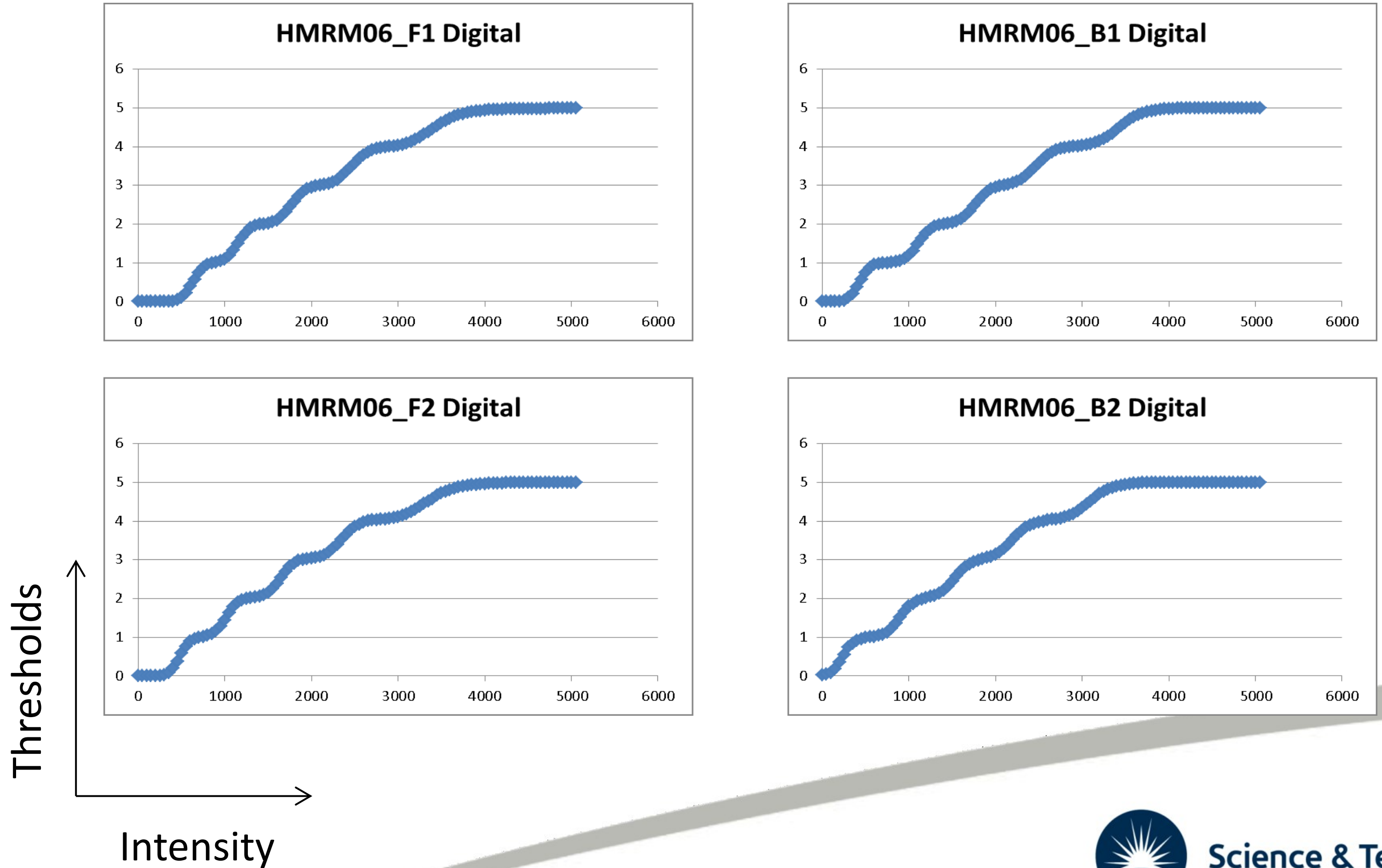
Performance summary of the low-res HMRM05 and HMRM06 ASICs:

	Gain (µV/e)	Mean Noise	Linear Full Well	Max Full Well	Gain (µV/e)	Mean Noise	Linear Full Well	Max Full Well
	Tests with 1 meter cable				Tests with 6 meter cable			
HMRM05_F_1	84.80	53.0	1689	3221	69.30	47.5	2069	3876
HMRM05_F_2	65.27	53.1	2088	4101	57.20	49.1	2349	4604
HMRM05_B_1	91.63	50.1	1752	3170	71.31	49.9	1869	3942
HMRM05_B_2	52.13	45.1	2645	5521	51.80	44.6	2944	5388
HMRM06_F_1	66.99	47.3	2166	4103	63.82	48.9	2366	4254
HMRM06_F_2	53.74	45.4	2565	4886	74.25	47.5	1813	3538
HMRM06_B_1	55.10	42.6	2832	5074	79.35	47.4	1872	3501
HMRM06_B_2	53.04	41.4	3083	5438	51.85	43.9	3058	5520
Average	65.3	47.3	2352	4439	64.9	47.4	2292	4328

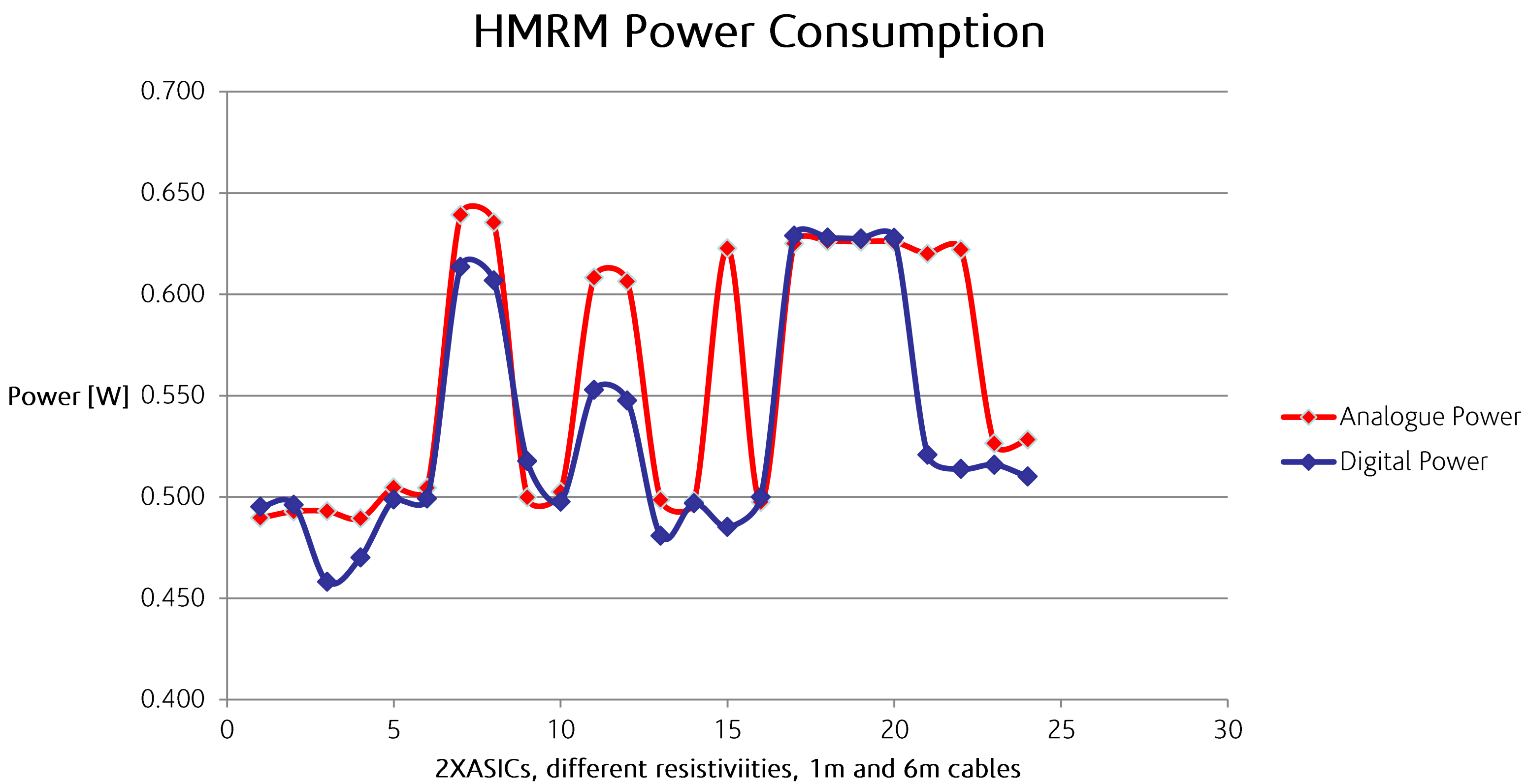
- Consistent performance of all ASIC in terms of gain, mean noise, linear and maximum full well. No significant differences between low-res and high-res ASICs.
- Noise is higher than expected due to analogue readout and not applied CDS (correlated double sampling).
- Gain variations are due to the noise on the power supply.
- Limited linear and max full well due to analogue readout. Should no be a problem with digital readout.

Sensor characterisation – digital readout

- Sensor has been irradiated with light at different intensities. 7 digital thresholds have been set up to detect light and Fe-55.



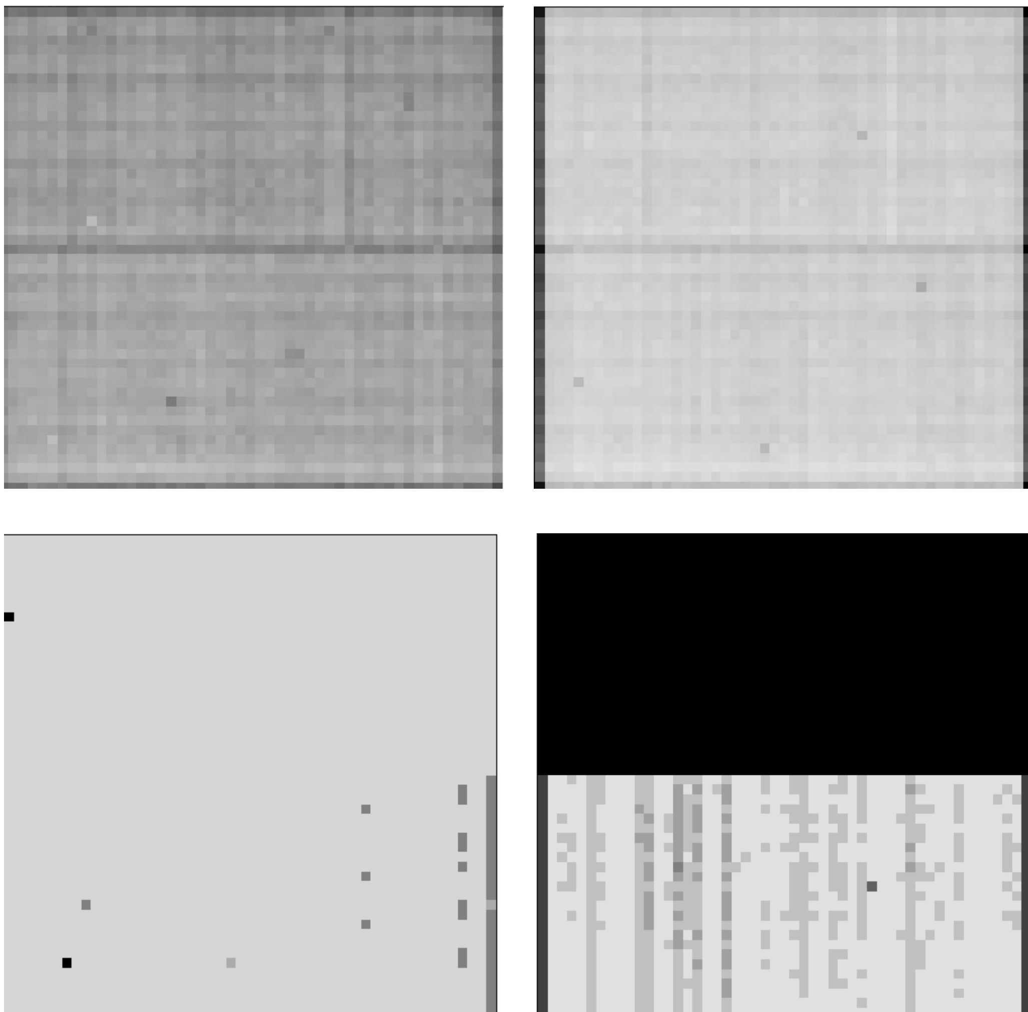
Power consumption



- 12 individual ASICs have been tested, 4 low-res and 8 high-res, different cables.
- Digital mode gives lower power consumption.
- Spread in the single ASIC power consumption is 0.23W – 0.32W.
- Mean power consumption for 1 ASIC is 0.28 W in analogue mode and 0.27 W in digital mode.
- Estimated power for whole HMRM (4 ASICs, voltage regulators, and FPGA+CAN circuity) = 1.93 W.

Tests with Fe-55 source

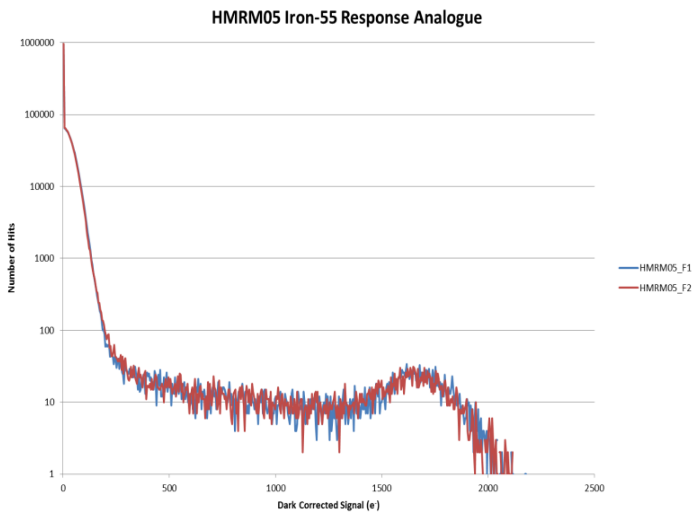
HMRM05 HMRM09

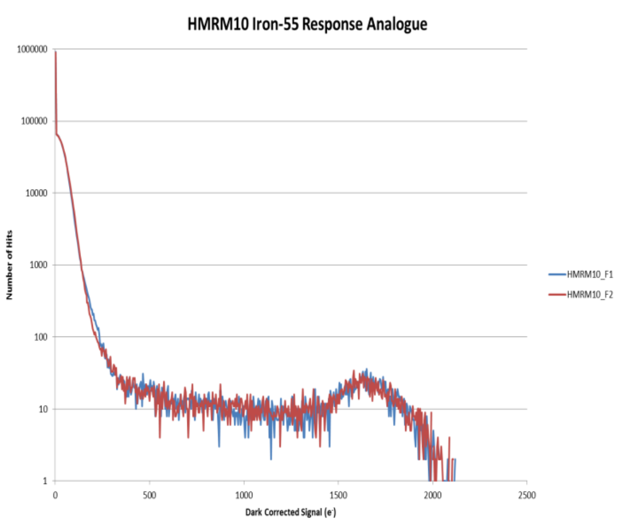


- Tests were conducted for HMRM05-HMRM10.
- 1000 imagers have been collected and used for analysis of energy deposition in the sensor with 3x3 pixels window analysis.
- Top: example of analogue readout; bottom: example digital readout, right: low-res HMRM06, left : high-res HMRM09

Tests with Fe-55 source – analogue readout

Example of sensor’s signal response histogram for Iron-55 irradiation

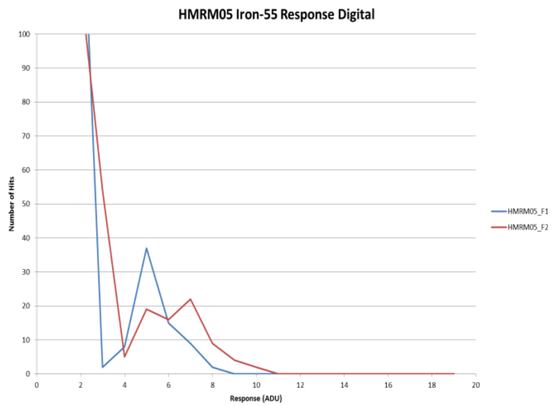


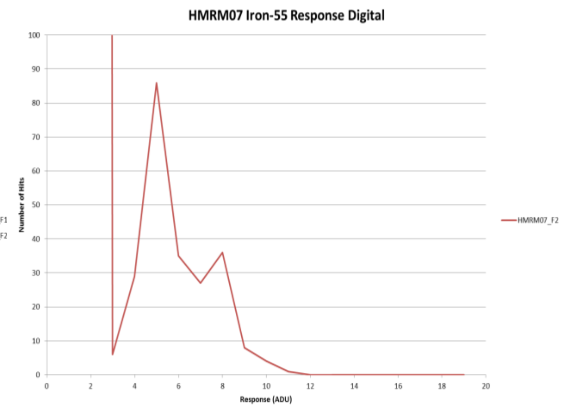


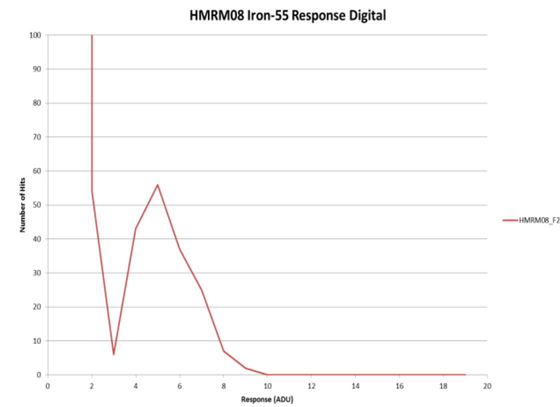
- Consistency of response on all sensors
- Main peak is in very good agreement with the expected from the photoelectrons from the 5.90 keV X-rays (expected 1616 e-).
- Secondary peak is expected at 10% level from 6.49 keV X-rays at 1778 e-.
- This peak is hard to detect due to noise.

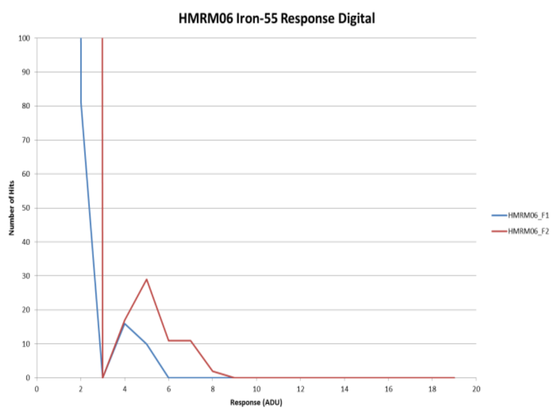
	F1, e-	F2, e-
HMRM05	1616.47	1664.47
HMRM06	1616.96	1647.12
HMRM07	1638.10	1673.37
HMRM08	1622.24	1580.38
HMRM09	1616.47	1599.01
HMRM10	1651.44	1587.01

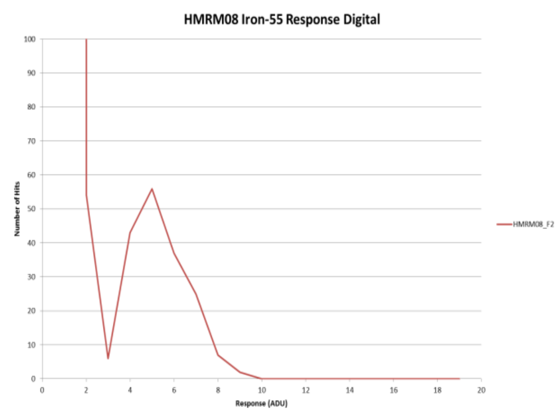
Tests with Fe-55 source – digital readout

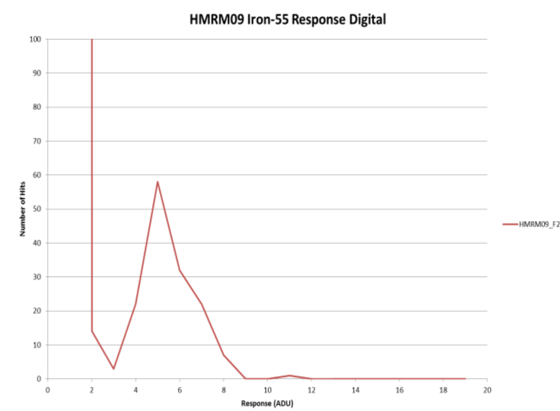










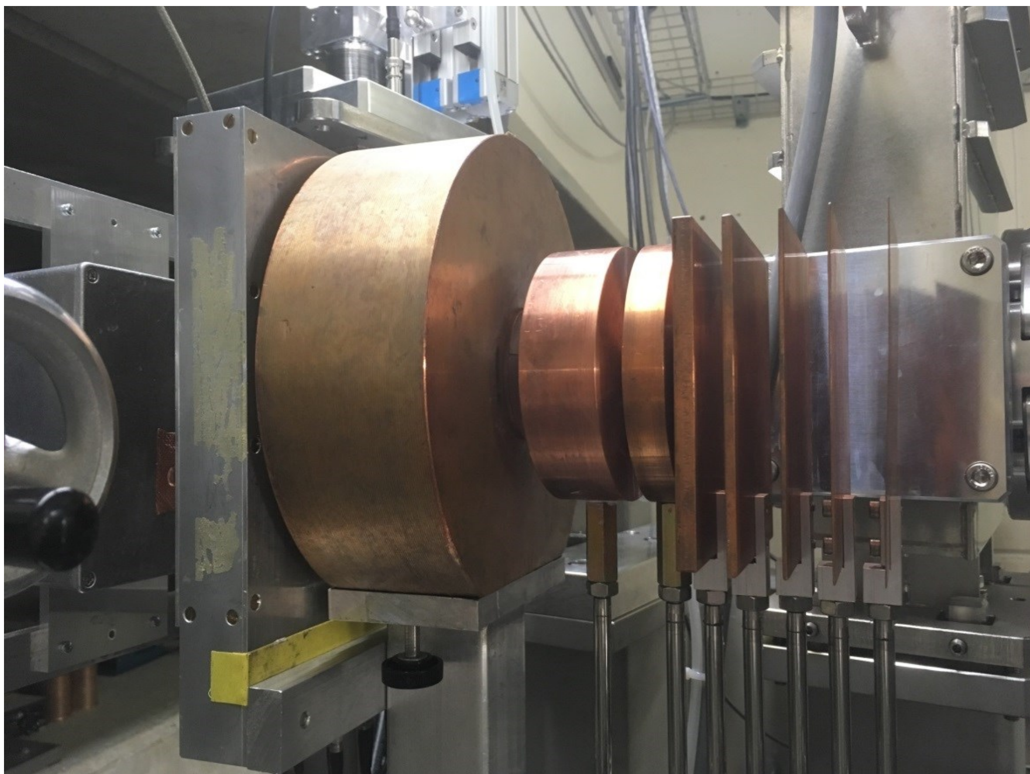


- Consistency of the response: sensors settings were adjusted in a way that Fe-55 main peak should be seen at threshold level 5.
- Other thresholds were optimised for Fe-55 and do not cover large range.

Tests with p⁺ beam line.

<u>The aims:</u>

- Functionality of new ASIC
- Analogue readout
- Multiple ASICs: consistency in performance



- Tests at PSI facilities.
- Collimated beam with 3 cm diameter.
- 8 Beam energies:

200 MeV, 180.3 MeV, 151.2 MeV, 130.7 MeV, 101.5 MeV, 80.4 MeV, 60 MeV, 29.3 MeV

- Tests of 2 low-res and 2 high-res devices
- Tests with analogue and digital readout
- 3000 images were collected for each E/device/readout mode.
- Low flux for 1 hit/frame: ~10^4 #/cm^2/s

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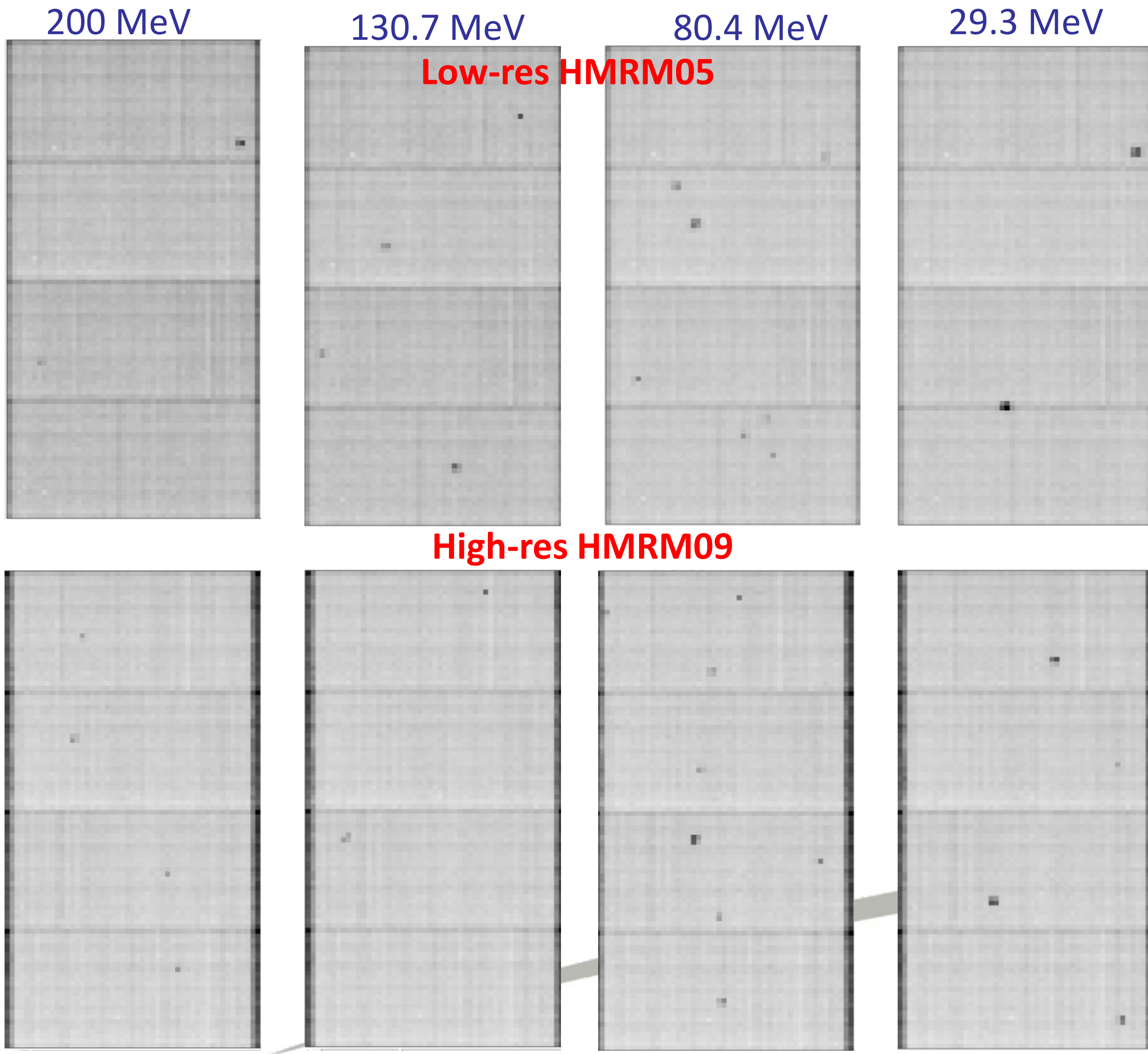
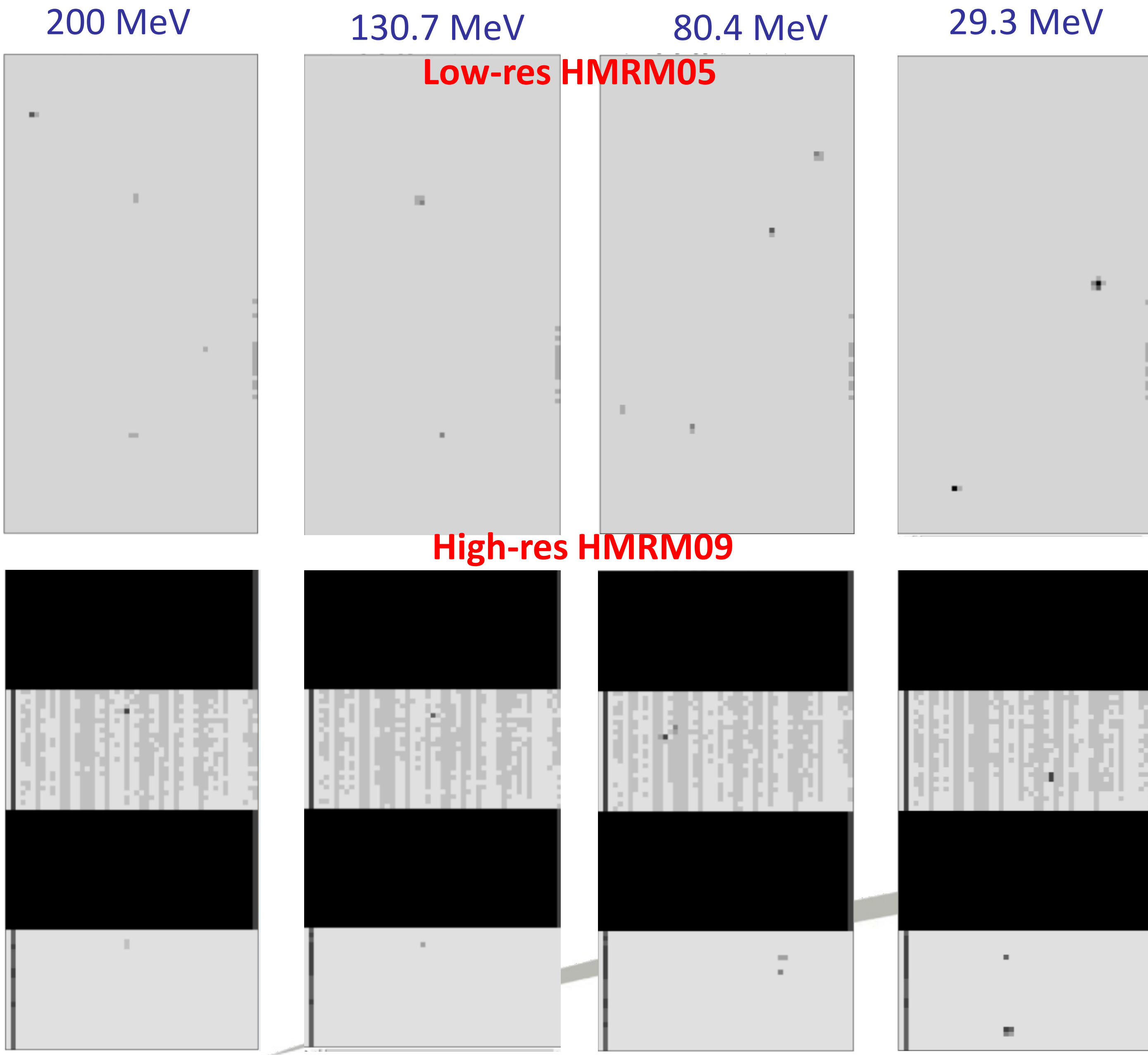
Analogue tests with p^+ source



- In general, signal is larger for lower energy p^+.
- Large spread of signal signatures.
- High-res ASIC shows less spread of charge.

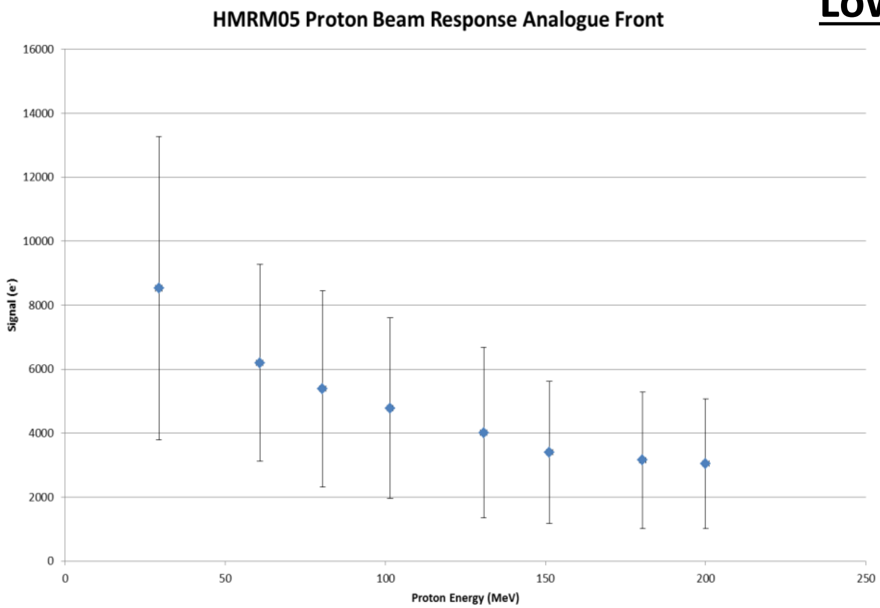
Digital tests with p^+ source

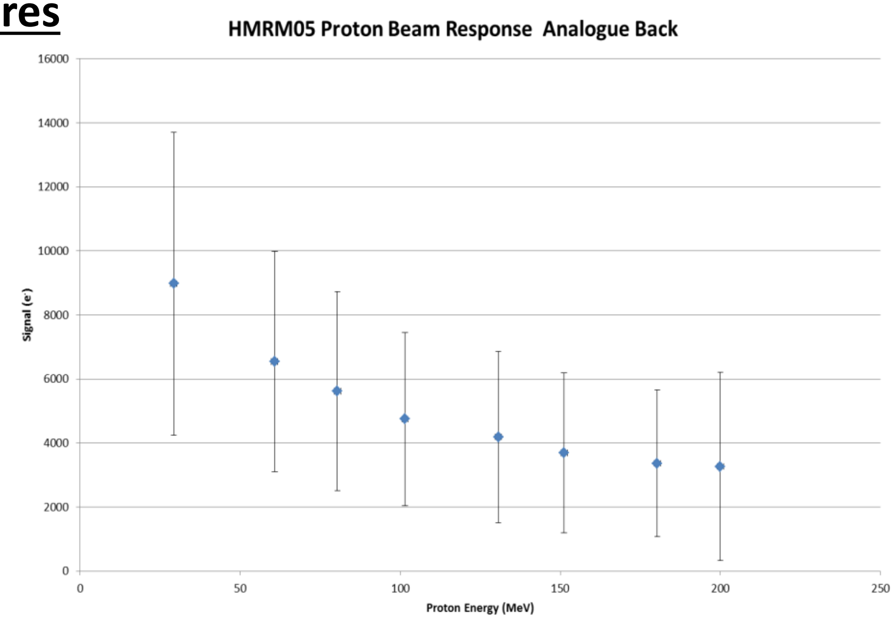


- In general, signal is larger for lower energy p^+.
- Large spread of signal signatures.
- High-res ASIC shows less spread of signal.

Analogue tests with p^+ source

Low-res





Energy (MeV)	Front Mean, e-	Front StDev, e-	Back Mean, e-	Back StDev, e-
200	3048	2026	3266	2942
180.3	3154	2137	3363	2293
151.2	3405	2221	3690	2500
130.7	4013	2669	4191	2677
101.5	4779	2822	4745	2698
80.4	5392	3067	5617	3110
60.8	6196	3078	6543	3435
29.3	8532	4732	8978	4732

- Expected increase of produced electron-hole pairs for lower energy protons.
- Similar performance of both ASICs.
- Large standard deviation, > 50% (in many cases > 60%)

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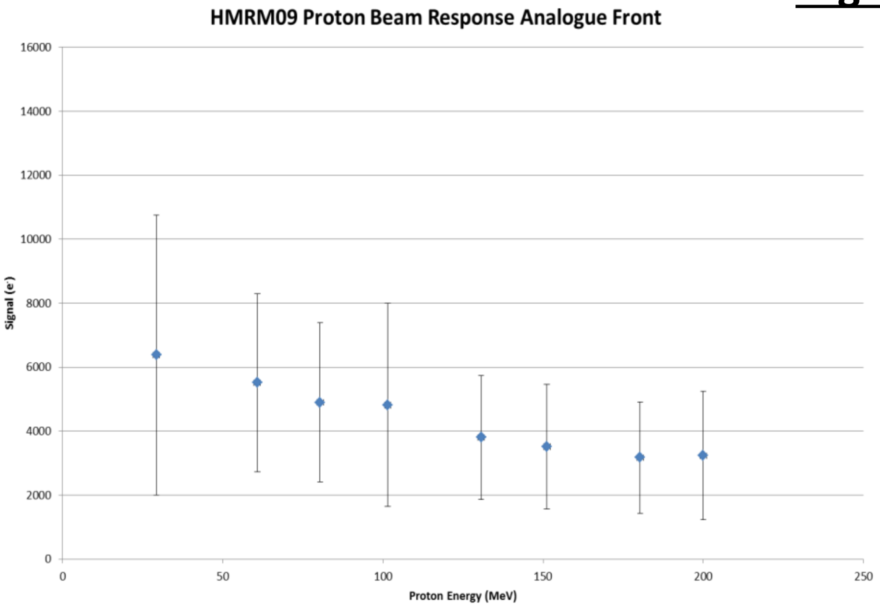
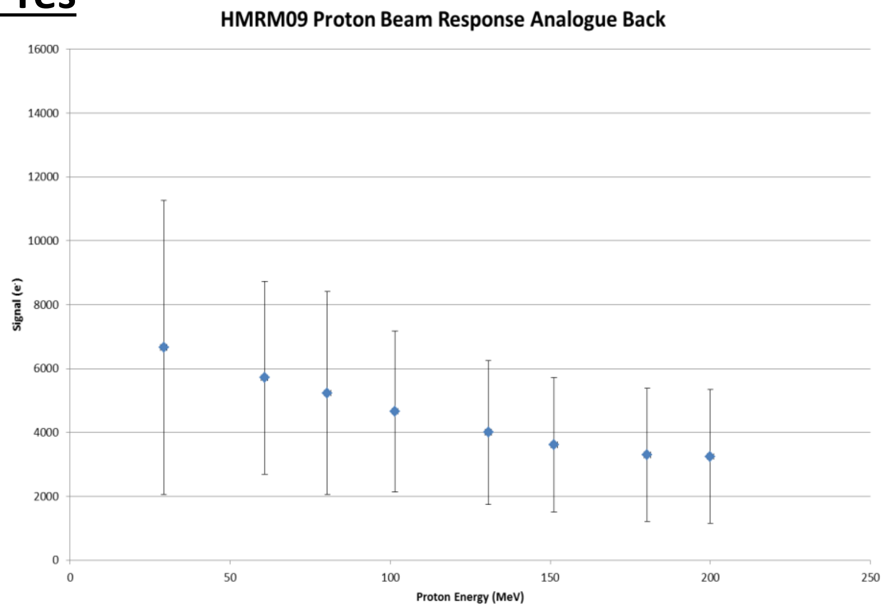
Analogue tests with p^+ source

High-res





Energy (MeV)	Front Mean, e-	Front StDev, e-	Back Mean, e-	Back StDev, e-
200	3235	2001	3248	2093
180.3	3176	1736	3301	2078
151.2	3519	1952	3616	2110
130.7	3802	1928	4006	2250
101.5	4816	3175	4661	2520
80.4	4899	2484	5236	3177
60.8	5514	2778	5709	3013
29.3	6379	4381	6660	4603

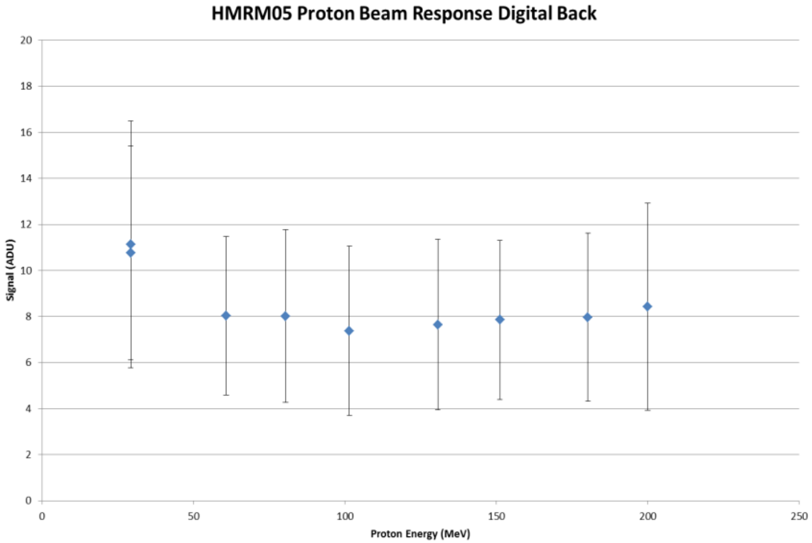
- Expected increase of electron-hole pairs production for lower energy protons.
- Similar performance of both ASICs.
- Large standard deviation, > 50%, but less than for low-res

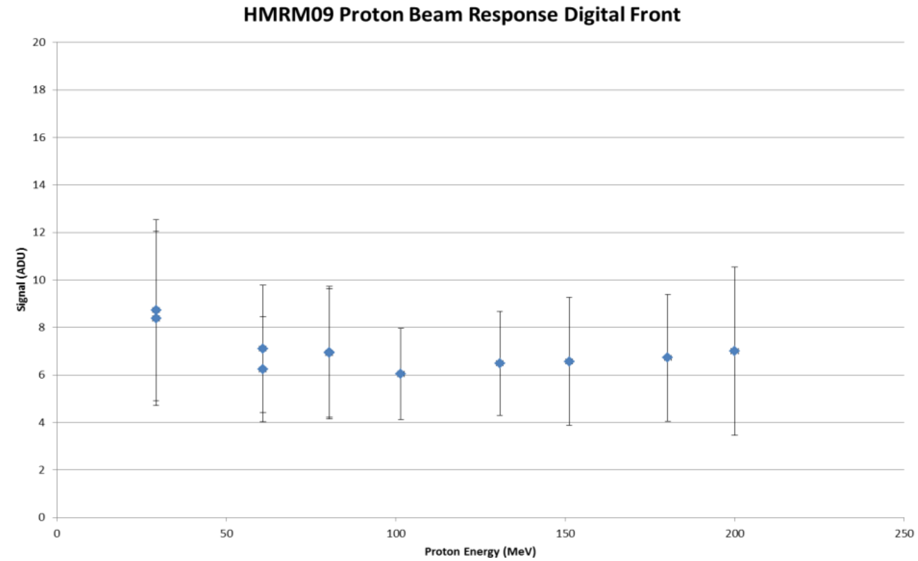
Tests summary of p^+ analogue readout

Energy (MeV)	Front Mean HMRM 05, e-	Back Mean HMRM 05,e-	Front Mean HMRM 06, e-	Back Mean HMRM 06, e-	Front Mean HMRM 09, e-	Back mean HMRM 09, e-	Front mean HMRM 10, e-	Back mean HMRM 10, e-	Expected at 12 µm, e-
200	3048	3266	3192	3493	3235	3248	3065	3201	2779
180.3	3154	3363	3219	3694	3176	3301	3214	3465	3028
151.2	3405	3690	4160	3954	3519	3616	3453	3691	3357
130.7	4013	4191	4077	4403	3802	4006	3897	4110	3810
101.5	4779	4745	5619	4999	4816	4661	4470	4861	4472
80.4	5392	5617	5400	5842	4899	5236	4906	5237	5274
60.8	6196	6543	6229	6681	5514	5709	5454	5731	6560
29.3	8532	8978	8664	9558	6379	6660	6428	6622	11252

- Consistency in the performance between same resistivity ASICs.
- Performance for 100-200 MeV p^+: low-res and high-res ASICs mean measurements agree very well with each other and theoretical predictions.
- Performance for 80-60 MeV p^+: mean measurements start to deviate between low-res and high-res ASICs, with high-res ASICs slightly undercounting e-.
- Performance for 30 MeV p^+: both low-and high-res ASICs significantly undercount e, problem is more serious with high-res ASIC.

Digital tests with p^+ source





Energy (MeV)	Front Mean HMRM 05	Back Mean HMRM 05	Front mean HMRM 06	Back mean HMRM 06	Front mean HMRM 09	Back mean HMRM 09	Front mean HMRM 10	Back mean HMRM 10
200	8.79	8.43	9.58	8.15	7.00	7.93	6.57	6.58
180.3	9.32	7.97	9.38	7.55	6.72	5.65	6.82	5.87
151.2	7.12	7.85	8.82	7.41	6.57	5.76	6.70	5.78
130.7	7.95	7.65	8.92	7.96	6.49	6.00	6.62	6.60
101.5	7.57	7.38	9.66	7.60	6.04	5.62	6.63	5.86
80.4	7.40	8.02	9.35	8.08	6.94	6.03	6.92	5.68
60.8	7.32	8.03	9.63	8.09	6.23	5.61	7.42	6.08
29.3	9.51	11.13	13.14	9.74	8.38	7.29	8.15	7.87

- Large signal standard deviation; No expected trend.

Results of the HMRM project

- Good technology with large potential for the future instrumentation.
- 3 generations of ASIC sensor have been produced and tested.
- Phase A/B was de-scoped to produce instrument based on stack of 2 sensors instead of 3 or 4. This configuration is not sufficient for reconstruction of particle spectrum from dE/dx method.
- The HMRM instrument based on 2-sensor stack of 2nd generation of ASIC was flown on the TechDemoSat-1 satellite.
- HMRM prototype based on the 2nd ASIC iteration was calibrated and tested with digital readout at PSI in 2015 :
  - 3-bit digital readout limits the accuracy of the reconstructed signal; charge sharing between the pixels needs more investigation.
  - High spread in the detector response.
  - Non-linear response at high flux.
- 3rd ASIC generation was developed with the aim to reduce power consumption, current ASIC version has a power consumption of 0.27 W per ASIC, corresponding to 1.93 W for total 4-sensor stack instrument. This is significant improvement from the 2nd ASIC.

Results of the HMRM project

- 2-stack configuration of 3rd generation of ASIC was tested for 2 high-res and 2 low-res substrates with Fe-55 and protons, concentrating on analogue readout.
  - The mean pixel noise was higher than expected and liner full well and maximum full well were smaller than expected. This is due to analogue readout.
  - All ASICs showed a clear primary peak for the Fe-55.
  - Consistency in the same resistivity ASIC performance.
  - ASICs performed as expected during the proton tests in the analogue readout, however the spread of the signal was high, with standard deviation > 50 % of the signal.
  - Both low-res and high-res ASICs significantly underestimated the expected production of electron-hole pairs for low-energy protons, 30 MeV.
  - Not satisfactory ASIC performance with the digital readout, partially due to threshold selection targeting the Fe-55 deposited energy region. The 3-bit digitisation producing 7 levels is very coarse and the reconstructed digital signal has a large error.

Results of the HMRM project

- Suggested way forward is a re-design of the instrument/ASIC concept:
  - Increase size of pixels
  - Reduce number of pixels
  - Different digitisation, 10-12 bits ADC
  - Simplifying assembly of the 4 sensors
  - Reduction of power supplies required
  - Geant4 modelling of the sensor response and charge sharing effects
  - COTS parts have been used for the FPGA. Use of space-qualified parts will increase the size of the instrument.

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