The MUSE Instrument Detector System

Roland Reiss, Sebastian Deiries, Jean-Louis Lizon, Gero Rupprecht
European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany

ABSTRACT

The MUSE (Multi Unit Spectroscopic Explorer) instrument (see Bacon et al., this conference) for ESO's Very Large Telescope VLT employs 24 integral field units (spectrographs). Each of these is equipped with its own cryogenically cooled CCD head. The heads are individually cooled by continuous flow cryostats. The detectors used are deep depletion e2v CCD231-84 with 4096x4112 active 15 µm pixels. The MUSE Instrument Detector System is now in the final integration and test phase on the instrument.

The paper gives an overview of the architecture and performance of the complex detector system including ESO's New General detector Controllers (NGC) for the 24 science detectors, the detector head electronics and the data acquisition with Linux Local Control Units. NGC is sub-divided into 4 Detector Front End (DFE) units each operating 6 CCDs. All CCDs are read out through 4 ports simultaneously to achieve short readout times at low noise levels.

All science grade CCDs were thoroughly characterized on ESO's optical detectors testbench facility and the test results processed and documented in a semi-automated, reproducible way. We present the test methodology and the results that fully confirm the feasibility of these detectors for their use in this challenging instrument.

Keywords: CCD, MUSE, VLT, characterization, optical, detector, instrument, spectrograph

1. INTRODUCTION

MUSE is a second generation instrument for the VLT. It is built by a consortium of European institutes and ESO. MUSE is an integral field spectrometer to be mounted on the Nasmyth platform of one of the VLT UTs. The Fore Optics splits a large field of view into 24 sub-fields. 24 Integral Field Units provide the spectral decomposition of the sub fields. Each IFU includes its own Instrument Detector Subsystem (IDS). The spectral coverage is 465 to 930 nm. Each IFU is equipped with its own cryogenically cooled CCD head. The detectors used are deep depletion CCD231-84 from e2v technologies with 15 µm square pixels and 4096x4112 active pixels.

2. INSTRUMENT DETECTOR SYSTEM (IDS)

2.1 IDS architecture

The Detector Controller (ESO's New General detector Controller NGC) consists of a total number of 24 Front-end Basic Boards (FEBs) distributed over four 6-slot housings. Each FEB contains an FPGA based programmable clock pattern generator (sequencer), programmable bias and clock driver circuitry, and a 4-channel video chain with clamp & sample circuits and 16-bit ADCs with 1MHz sample rate. Figure 1 shows an overview of a 6-slot NGC front-end electronics (DFE). Not shown in Figure 1 is the CCD preamplifier box which is located between the detector head and FEB. The preamplifiers have software programmable gain and bandwidth settings. Each 6-slot NGC is connected to and controlled by a dedicated Linux Local Control Unit (LLCU). The LLCUs are DELL PowerEdge 2950 rack mountable PCs with a PCI fibre interface board.

In Figure 2 the global layout of the IDS for 24 detectors and the corresponding boards and LLCUs is shown. The DFEs are located on the top of the Instrument Main Structure (IMS) on the Nasmyth platform of UT4, the LLCUs are located inside a dedicated cabinet on the azimuth platform (AP). The four DFEs and the LLCU cabinet are actively cooled to meet the VLT environmental specifications.
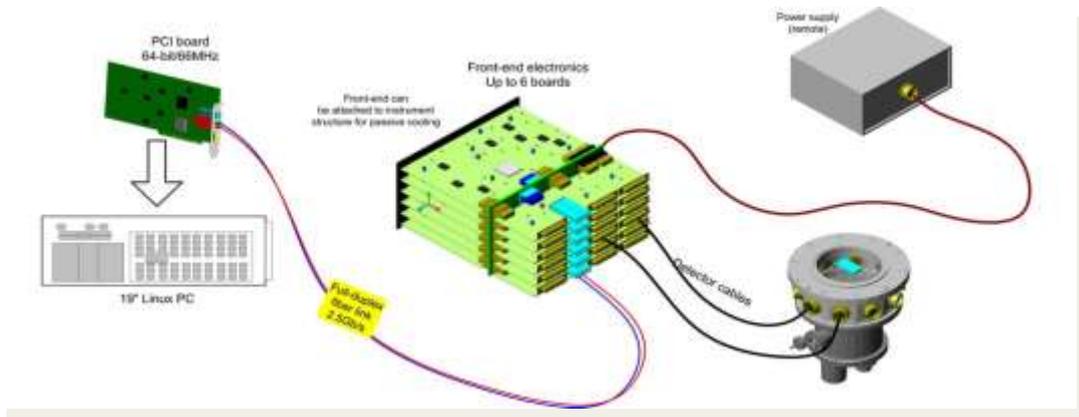
Figure 1. Simplified schematic overview of one 6-slot NGC system.

In summary the MUSE IDS is built from the following sub-components:

- 24 e2v frame transfer, 4096x4112 15μm pixel, CCD231-84 2Kx4K Deep Depletion Silicon CCDs, one for each of the 24 IFUs, read out with different binning modes.
- 24 ESO standard Detector Heads (DH) and Continuous Flow Cryostats (CFC). The DHs contain CCD filter and buffer circuits on rigid-flex printed circuit boards.
- Four NGC Detector Front Ends (DFEs) each consisting of six Front End Basic boards (FEBs) and six Transition Boards mounted in a six-slot liquid cooled housing.
- 24 pre-amplifiers
- Four standard NGC Power Supply Units (PSU) in air cooled housings plus cables.
- 24 cable sets to connect the FEBs to the detector heads.
- NGC providing the shutter control signals from the shutter/trigger connector on transition board #1 of NGC #1. The shutter control signal is fed to the Bonn Shutter Controller.
- Four LLCUs, NGC interface boards and CCD-DCS software.
- 4 optical fibers connecting DFEs and LLCUs.
- Instrument Workstation (IWS) to collect and assemble image data.
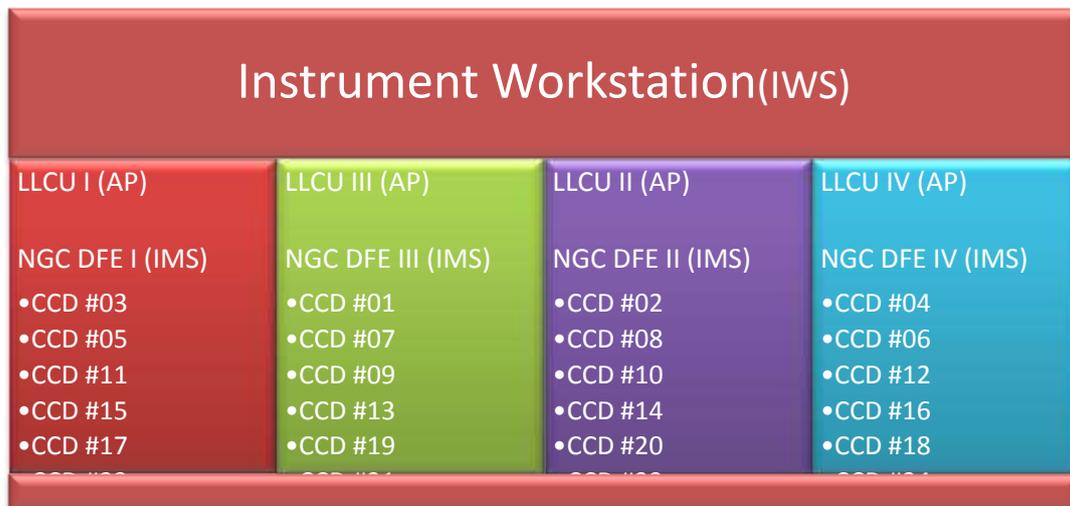
Figure 2. MUSE IDS Global layout.

Figure 3 shows one of the four NGC front-ends in its water-cooled housing. This is the rear view onto the Front End Basic Transision Boards (FEBT) which carry the connectors for video (left) and clocks and biases (right). The lower of the six boards is equipped with a fibre-optic transceiver which is used for the connection to the LLCU.

Figure 3. 6-slot NGC detector front-end

2.2 CCD architecture

The CCD (see Figure 4) has an image area with 4096x4112 active pixels, split readout registers at both top and bottom with charge detection amplifiers at both ends (ports EFGH). The pixel size is 15 μm square. The image area has four separately connected vertical sections (ABCD) to allow full-frame, frame transfer, split full-frame or split frame-transfer modes. Depending on the mode, the readout can be through one, two or four of the output circuits. The main science readout mode of MUSE uses all four outputs.

The output amplifier is designed to give very low noise at readout rates of up to 3 MHz. The low output impedance simplifies the interface with external electronics and the optionally usable dummy outputs are provided to facilitate common mode rejection. More details about the device architecture and the (dummy) outputs can be found in the e2v CCD231 datasheet [1].
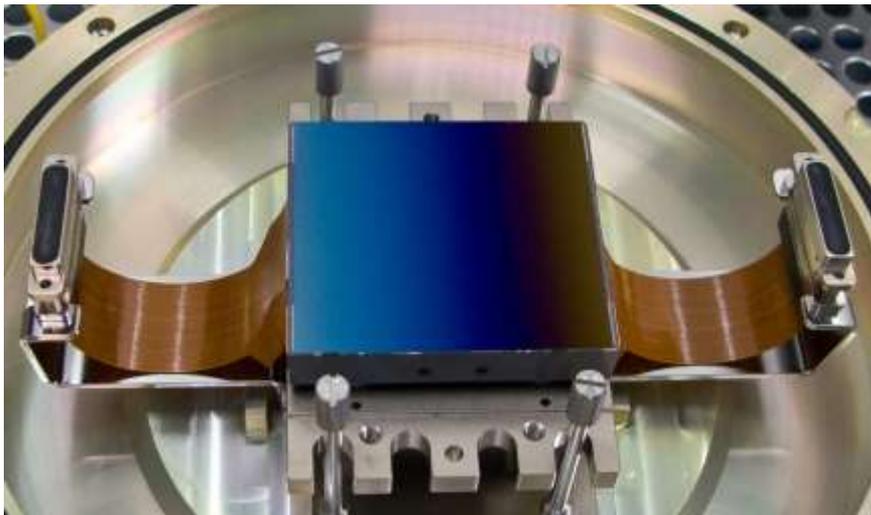
Figure 4. CCD with graded AR coating shown in its shipping container.

3. DETECTOR HEAD ELECTRONICS

The rigid-flex Printed Circuit Board (rigid-flex PCB) located in the Detector Head (DH) (Figure 5) is the mechanical and electrical interface between the DH hermetic connector and the CCD connectors "Connector 1" and "Connector 2". The rigid-flex PCB contains filters for clocks and biases as well as junction FET (JFET) output buffers for the 4 "real" and the 4 dummy outputs. The mechanical design of the Detector Head is described in detail in [2].
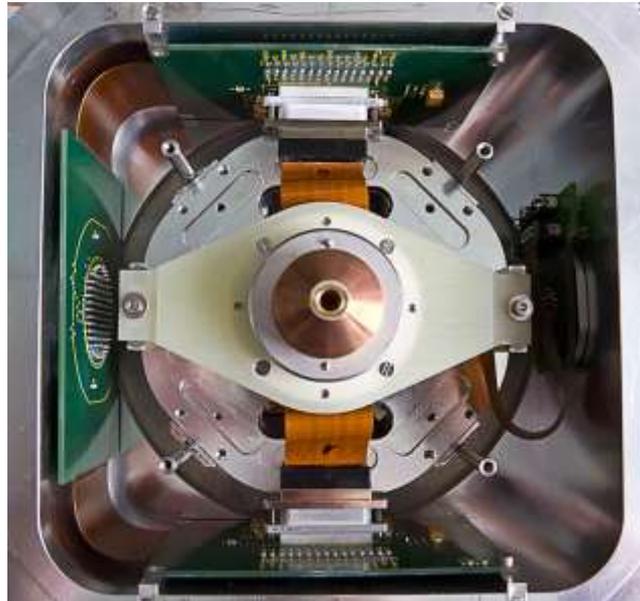
Figure 5. Bottom view of the rigid-flex printed circuit board with CCD filter and buffer circuits.

Figure 6 shows the buffer circuit for one output port. Schottky diode D1 prevents shorting of DOS and OS through the JFET junctions (Q1, Q2) in case of supply voltage (JD) failure. The dummy and real outputs are loaded with 10kΩ resistors located closely to the CCD connectors. As we did not encounter any serious pickup problems we decided not to use the dummy outputs for MUSE. Using the dummy outputs would have a noise penalty of a factor of about √2.
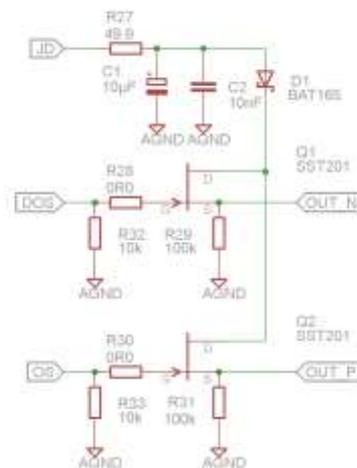
Figure 6. JFET Output Buffer (JD: supply voltage, DOS: CCD dummy output, OS: CCD output).

Figure 7 (left) shows the schematics of a typical bias filter. All unipolar bias (VOD, VRD, VDD) filter circuits are equipped with protective Schottky diodes which prevent negative bias voltages with respect to substrate (VSS). Negative drain voltages could damage the device. The filter time constants correspond to approx. 100 times the maximum pixel period, i.e. 100x10μs = 1ms. Figure 7 (right) shows the schematics of a typical clock filter.
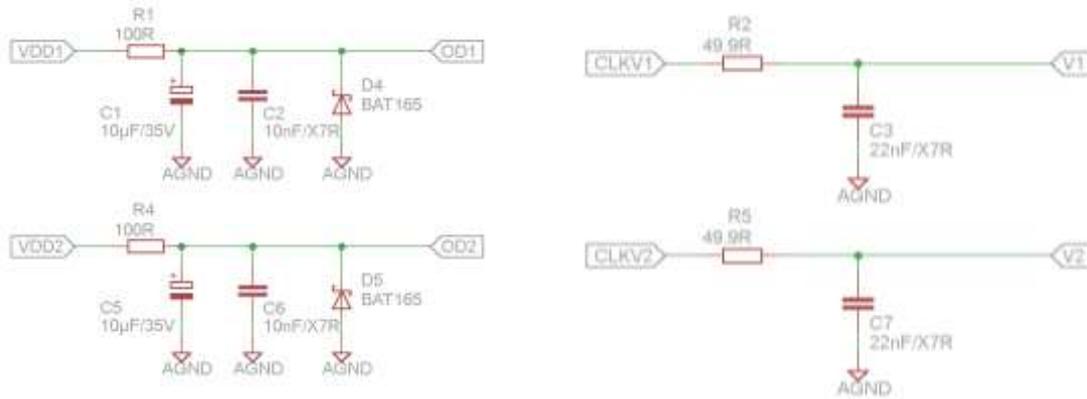
Figure 7. CCD bias (left) and clock (right) filters.

The filter time constants are selected to provide the recommended clock rise and fall times (Table 1).

Table 1. Typical recommended clock rise and fall times.

Clock signal	Rise time	Fall time
Transfer gate	2 μs	n/a
Image (parallel) clock	2 μs	2 μs
Register (serial) clock	20 ns	20 ns
Reset pulse	10 ns	10ns

3.1 Operating modes

Table 2 shows the standard readout modes implemented for the MUSE instrument. There are two modes with low and high gain with 100kpix/sec pixel rate and one mode with low gain and 500kpix/sec. There is an additional overhead for data transfer from the LLCUs to the IWS and merging of the 24 detectors into a single FITS file of approximately 10sec at binning 1x1. Table 2 shows the binning factors which are officially supported for MUSE. However, NGC offers any combination of binning for the CCD231.

Table 2. Operating modes and readout times

Mode	Ports	Pixel rate [kpix/sec]	typ. Gain [e-/ADU]	typ. Noise [e-RMS]	Readout time at different binning settings [sec]				
					1x1	2x2	2x4	4x2	4x4
SCI 1.0	EFGH	100	1.0	2.2	45.6	13.5	7.1	8.4	4.6
SCI 0.7	EFGH	100	0.7	2.1	45.6	13.5	7.1	8.4	4.6
FAST	EFGH	500	1.0	4.3	9.8	3.7	2.3	2.9	1.9

3.2 Thermal control

The hardware and performance of the Vacuum and Cryogenic System (VCS) for the MUSE detectors is described in detail in [1]. One essential part of the VCS is the Detector Vessel (DV) controller named TeePee (for Temperature and Pressure). The DV consists of the DH and Continuous Flow Cryostat (CFC). DH and CFC together contain four Pt100 thermal sensors and one Edwards Wide Range Gauge (WRG) vacuum sensor. The thermal sensors measure the temperatures of the detector, cold plate, exhaust gas and sorption pump. TeePee (Figure 8) is built from commercial off the shelf components. Its main component is a JUMO Imago 500 Program Controller. The Imago 500 takes care of converting the Pt100 and WRG signals into temperature and pressure readings. There are three PID (proportional, integral, derivative) control loops active during normal operation. A forth PID controller is used during the regeneration of the sorption pump. The temperature of the cold plate is controlled by turning on or off the LN2 flow by a magnet

driven regulating valve. The temperatures of the heaters (detector, exhaust gas and sorption pump) are controlled by heating resistors and solid-state relays. The thermal stability of the cold plate is in the order of a few °C, while the detector temperature is kept well within 0.1°C. The Imago 500 has a built-in recording function for 4 analog and three digital signals. The recording function allows to analyse data up to 10 days back in time. As can be seen in Figure 8 one TeePee serves two detector heads and cryostats.

Figure 8. TeePee front view

More details about the Vacuum and Cryogenic system of MUSE can be found in [3].

4. TEST RESULTS

4.1 Component level tests

All performance critical subcomponents like FEBs, preamps and cables have been tested on an individual basis: That is one at a time, on the ESO ODT testbench using a standard photon transfer calibration at fast and modes listed in Table 2 prior to assembly of the four MUSE DFEs.

4.2 Detectors

A total of 28 CCD231 (25 science grade, 3 engineering grade) were mounted under clean room conditions in their detector heads and subsequently tested on the ESO Optical Detector Lab (ODT) testbench facility. Most of the tests (i.e. gain noise, linearity, QE, dark current) are performed in a fully automatic and standardized way under the control of PRiSM[1] scripts. Table 3 summarizes the most import results like quantum efficiency, readout noise, linearity, dark current, cosmic ray event rates and flatness obtained with the 28 CCDs.

Table 3. Results of detector characterization

	QE @				RON	LIN	DC	Cosmics	Flatness
	500nm	700nm	900nm	930nm	[e-RMS]	[%]	e-/pix/h	events/min/cm^2	[μm PtV]
Specification	**> 0.8**	**> 0.75**	**> 0.4**	**> 0.4**	**< 3**	**< 0.5%**	**< 3**		**< 20**
Maximum	0.960	0.967	0.701	0.482	2.910	0.600	3.900	2.200	12.900
Average	**0.931**	**0.942**	**0.625**	**0.429**	**2.296**	**0.306**	**1.468**	**1.992**	**7.956**
Minimum	0.884	0.900	0.541	0.376	1.950	0.100	0.100	1.800	3.600
Std. Dev.	0.021	0.022	0.030	0.020	0.318	0.118	0.931	0.108	2.780

Readout noise (and gain in e⁻/ADU) was measured with the usual photon transfer method. As can be seen in the table above the variations across all output amplifiers was fairly small. The value of 2.91 e⁻RMS was in fact an outlier of a single output amplifier out of 112 measured in total.

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[1] http://www.prism-astro.com/us/index.php

The **Dark Current** measurements showed somewhat larger variations across the tested devices, mainly due to small light leaks in the testbench. The results improved after a Bonn Shutter[2] was installed directly in front of the detector housing as a replacement for the iris shutter at the monochromator exit slit.

Figure 9 shows a plot of the **Quantum Efficiency** of three different devices (named Juno, Psyche and Urania). The figure shows the small variation of QE across the wavelength range of the MUSE instrument (465 to 930nm). The QE measurement is done on the PC controlled ODT testbench. The calibration standards used were calibrated photo diodes from Hamamatsu.
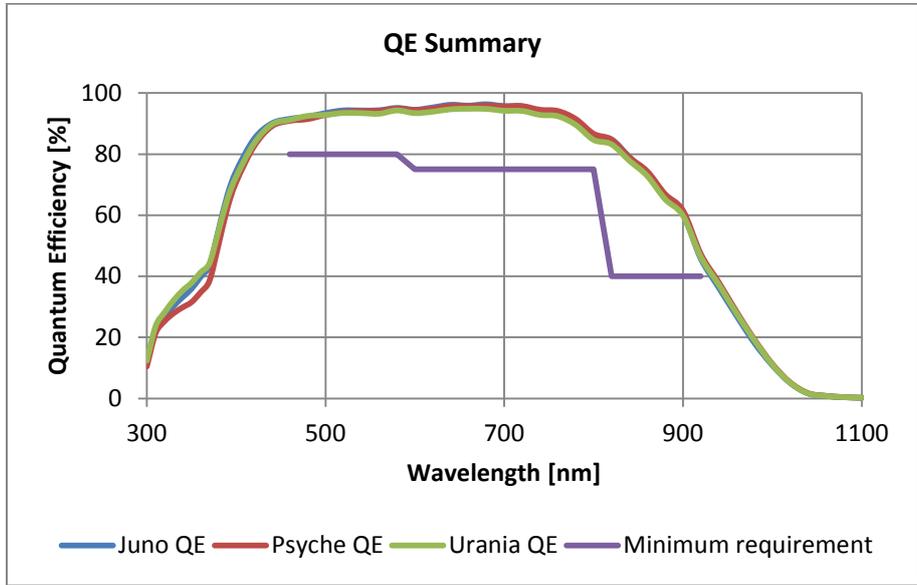
Figure 9. Quantum efficiency of three devices

Remanence has been observed with one of the engineering devices if clocked in normal (*non-inverted*) mode. If the CCD is heavily overexposed (in excess of 500ke⁻) subsequent dark frames show ghost images which take hours to disappear again. Reading several frames in *inverted* mode seems to drastically shorten the recovery time. In a dark frame taken directly after overexposure with 8 times vertical binning and 450s integration time an average remanence signal of 60e⁻ was measured. Another dark frame taken after one hour still shows a level of about 40e⁻. After two short dark frames taken immediately after overexposure with *inverted* clocks the subsequent dark frames in standard mode did not show any ghosts anymore.

Remanence could not be observed using inverted clocks during integration and readout. Inverted clocks are therefore the preferred setup for MUSE.

Port-to-port crosstalk has been measured with a precision slit exposing only one quadrant on the CCD with a bright diagonal line. At signal levels up to 65ke⁻ (saturation of the 16-bit ADC at 1e⁻/ADU) the crosstalk is below the noise floor and therefore invisible. At signal levels close to the blooming level (300ke⁻) crosstalk is in the order of a few electrons (typically 7e⁻). Tests have been made by exposing CCD quadrant F and visually inspecting the quadrants E,G and H.

The **Point Spread Function** (PSF) was measured on a small sample basis (4 devices out of 28) by projecting a small spot with a diameter of a few microns onto the CCD. This spot is then moved across several pixels along rows and columns by a PC-controlled X-Y-Z stage and the data is processed using a PRiSM script.

The PSF measurement is done for scan directions in X (along rows) and Y (along columns) and for different values of the collection phase voltage Vc. This is the "high" value of the vertical clocks. The "low" value of the vertical clocks remains unchanged and is at -8V for all MUSE CCDs.

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[2] http://www.bonn-shutter.de/index.php

Measurements of PSF have shown good results (Figure 10). The MUSE specification (1pixel FWHM at 500nm and below; 0,6 pixel FWHM at 700nm and above) is fulfilled, except at 700nm where PSF is marginally higher. A collecting phase voltage (Vc) of 2V and integration on 2 vertical phases was chosen.
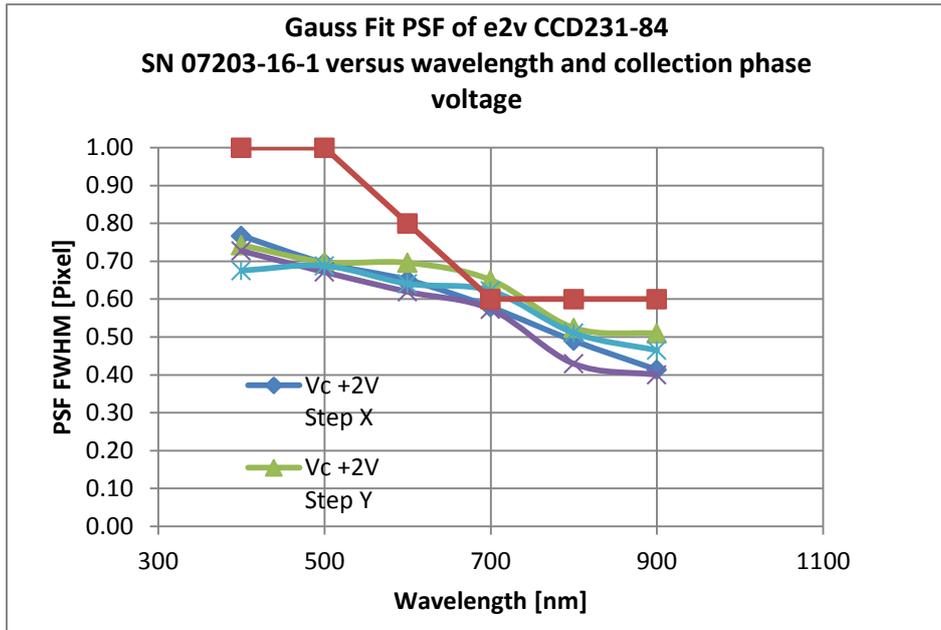
Figure 10. Point Spread Function vs. wavelength and collection phase voltage

5. CONCLUSION

The MUSE IDS has demonstrated excellent performance and fully meets the requirements of the MUSE instrument. The DFE is capable to read 24 CCDs with a total of 96 outputs in less than a minute with a noise level of $2e^-$RMS. The 28 CCD detectors tested in total showed a very uniform and state-of-the-art performance with little variations from device to device.

REFERENCES

[1] e2v technologies, CCD231-84 datasheet, <http://www.e2v.com/>
[2] Lizon, J. L. et al., "A series of detector systems for MUSE", Proc. SPIE 8446-192
[3] Lizon, J. L. et al., "Detector Vacuum and Cryogenic System for MUSE", Proc. SPIE 8446-217