A system for characterization of DEPFET silicon pixel matrices and test beam results

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On behalf of the DEPFET Collaboration

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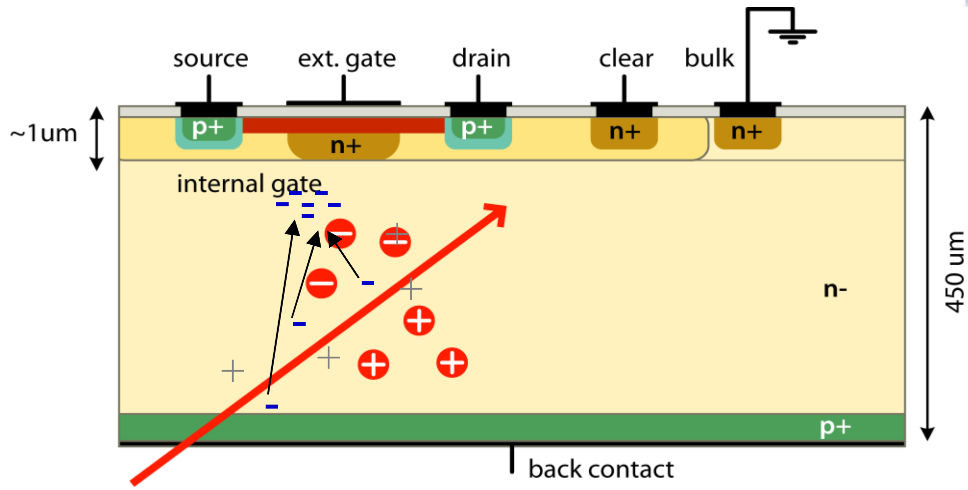
Outline

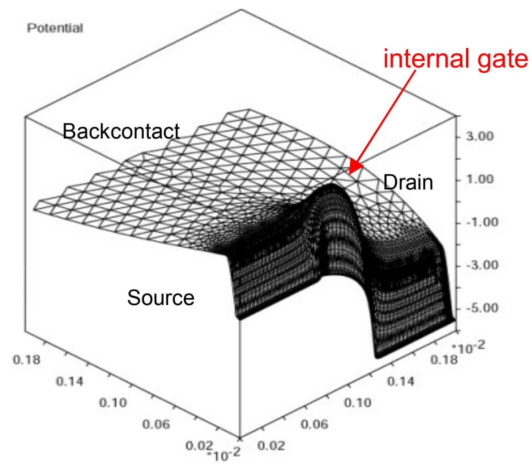
- *Introduction to DEPFET readout*
  - The principle of DEPFET
  - Readout electronics
  - Data acquisition system (DAQ)
  - Online monitoring (DQM)
- *Characterization of DEPFET matrices*
  - Lab measurements : Laser and Am^{241} source
  - Test Beam Setup at CERN
- *Data analysis software*
- *Test Beam results*
- *New developments*
- *Conclusion*

The Principle of DEPFET

- *The DEPFET is an active pixel sensor which integrates a MOSFET into the high resistivity silicon substrate*
  - in-pixel amplification
- *Electrons are collected in "internal gate" - potential minimum for electrons - and modulate transistor current*
- *Transistor can be switched off by external GATE – charge collection still active !*
- *Charge from internal gate is removed via CLEAR contact*
- *Low readout capacitance – reduces the noise*
- *Provides fast charge collection in fully depleted bulk*
- *more about DEPFET: www.depfet.org*



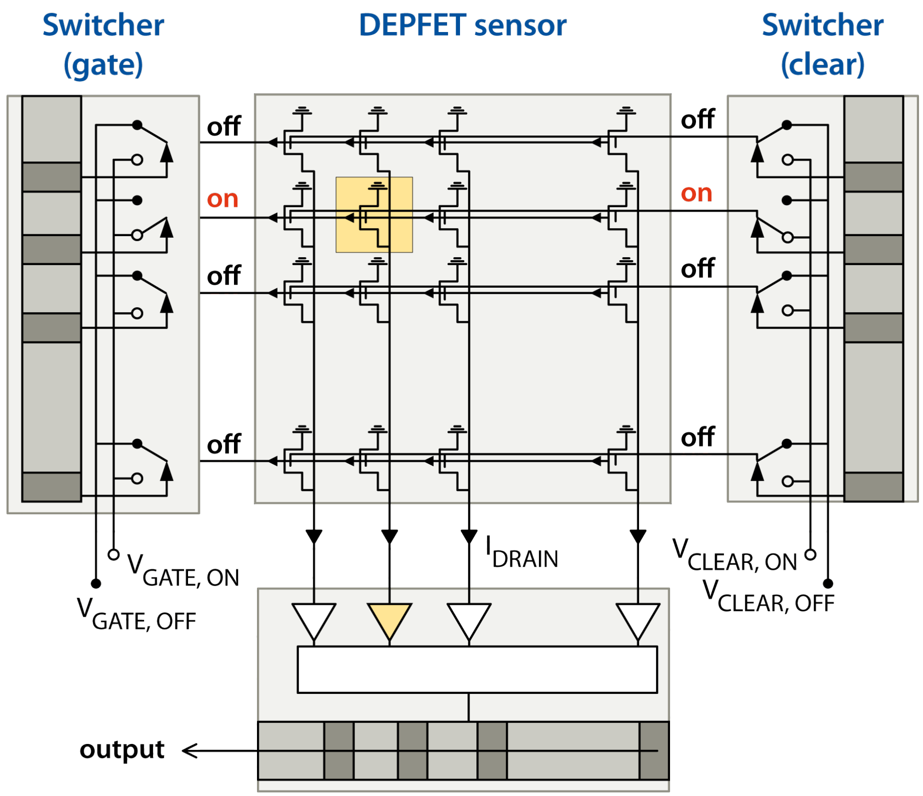
Potential distribution

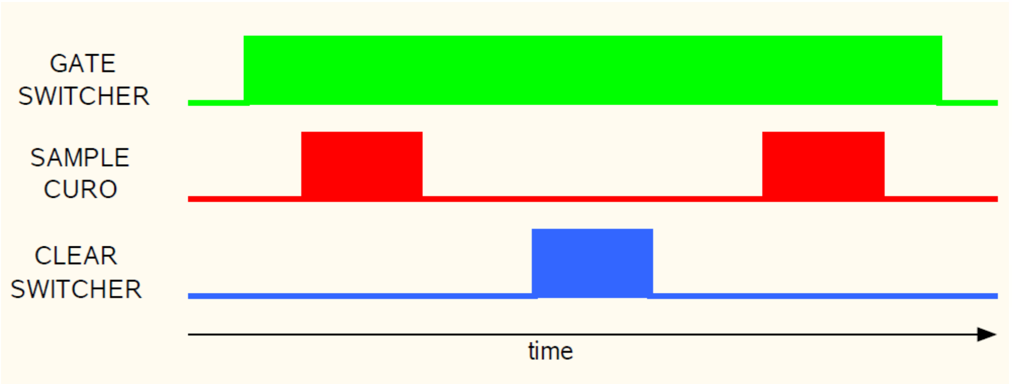


[ToSCA-Simulation]

DEPFET readout sequence

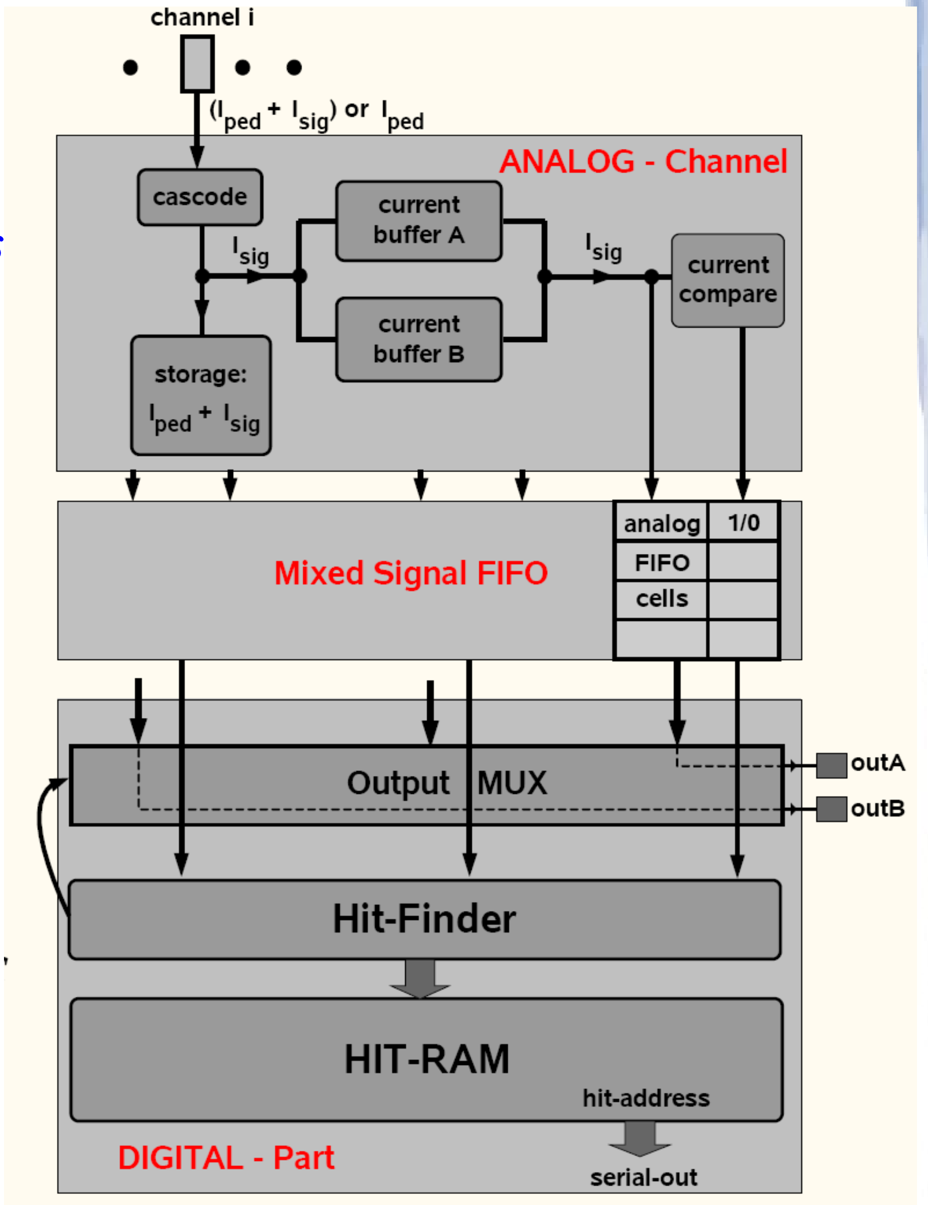
- *Sources of transistors are connected to common potential*
- *Gates are connected row-wise*
- *Drains are connected column-wise*
- *Readout chip CURO processes all columns in parallel*
- *The SWITCHER chip generates the steering signals for the rows - GATE and CLEAR.*
- *DEPFET readout sequence :*
  - select row with external gate
  - readout transistor current : I_sig + I_ped
  - clear charge from internal gate
  - again readout transistor current: I_ped
  - subtract pedestal current
  - select next row



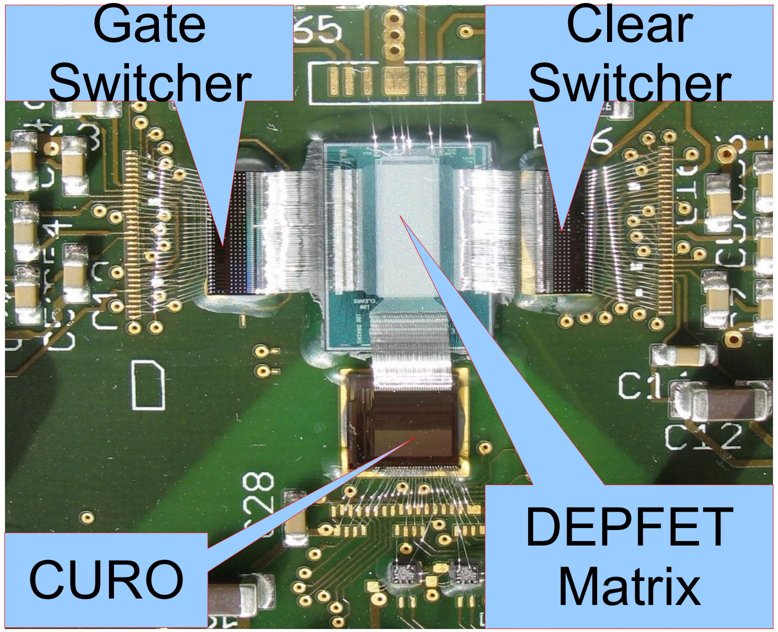


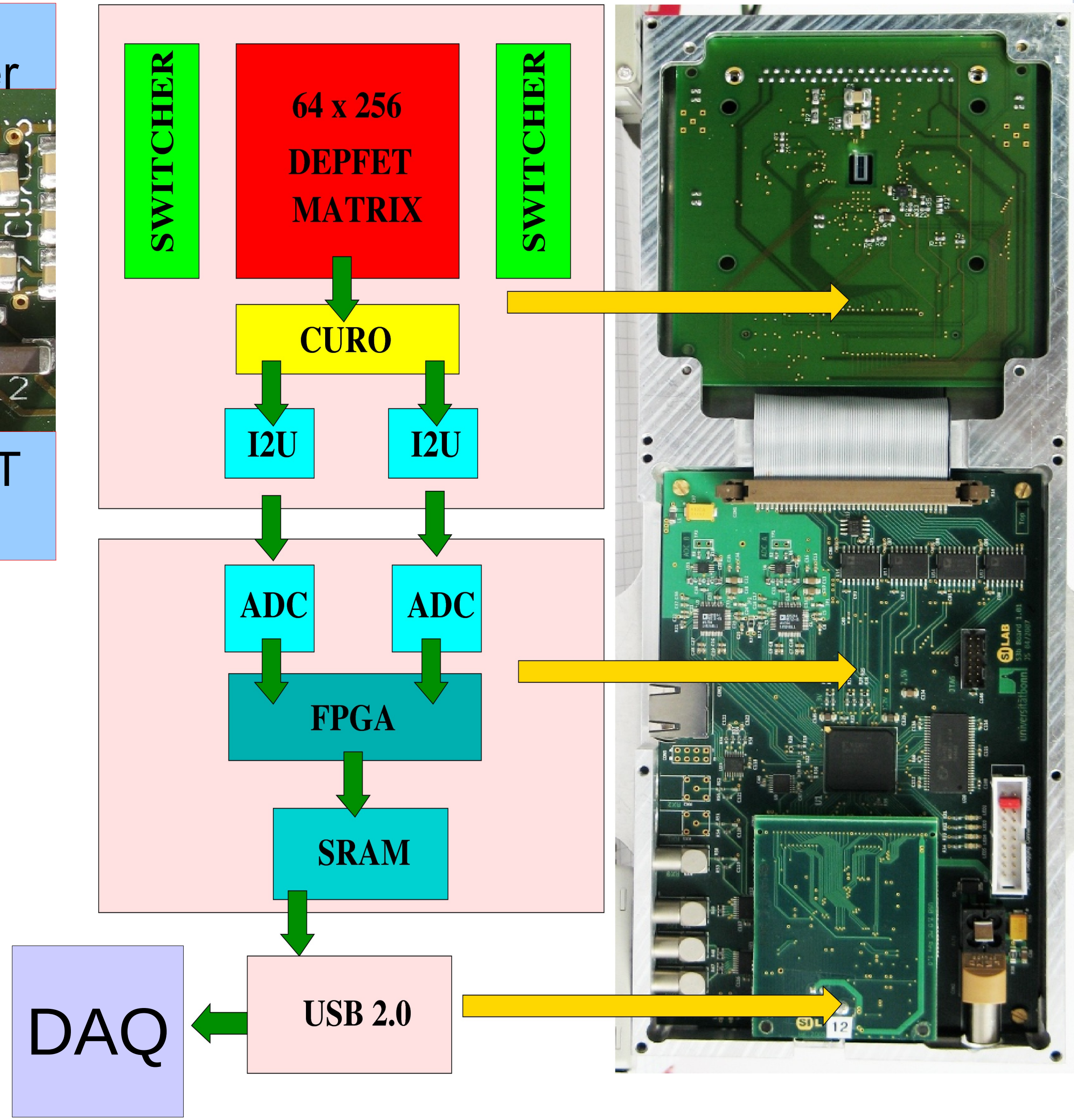
Readout chip CURO

- *CURO – CUrent ReadOut - consists of :*
  - current memory cells
  - current comparator
- *Current based readout with regulated cascodes*
- *CURO readout can work in 2 modes:*
  - readout all pixels – row by row
  - zero suppression mode (not used)
- *typical time scale for sample-clear-sample ~320 ns*
- *the general control of readout is managed by FPGA on readout board.*
- *the output of CURO is digitized by a 14 bit ADC and stored in SRAM for a subsequent readout.*



DEPFET readout board

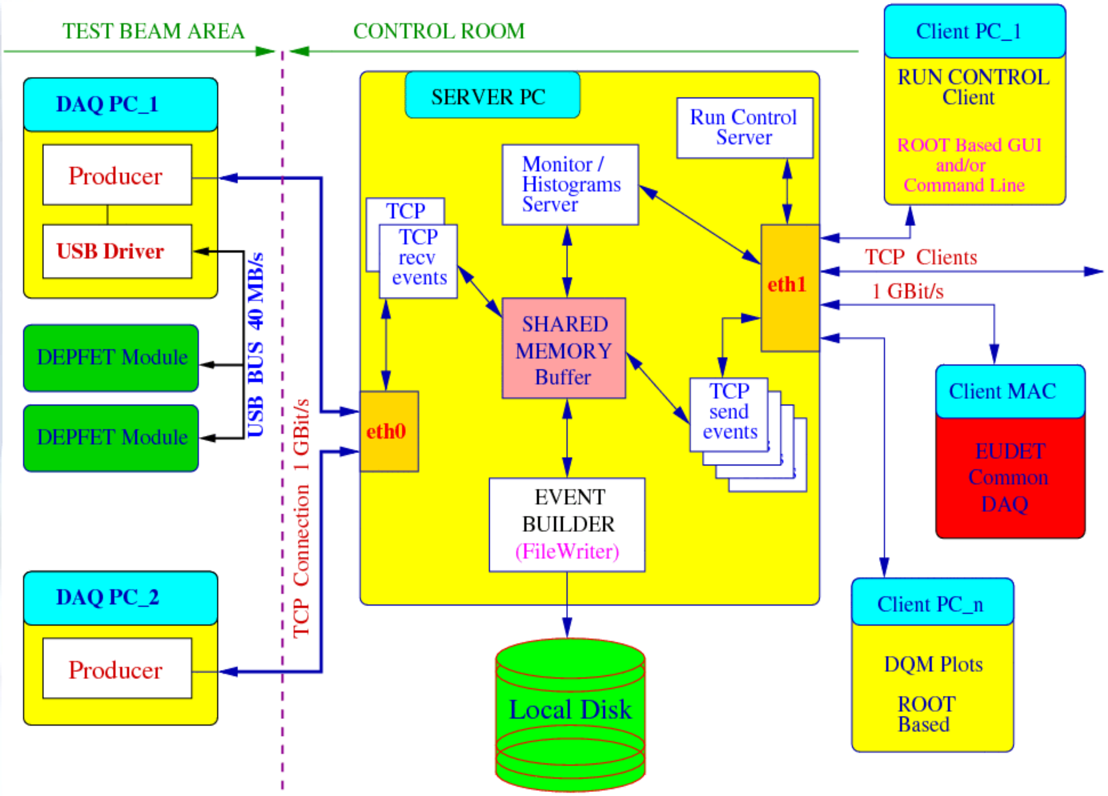




- *A second board (S3B) contains :*
  - FPGA
  - ADCs
  - buffer RAM
  - USB2.0-PC interface.
- *S3B board provides the read out rate up to 130 Hz*
  - Data rate about 4.2 MB/s per module (32 kB / frame)

Network DAQ System

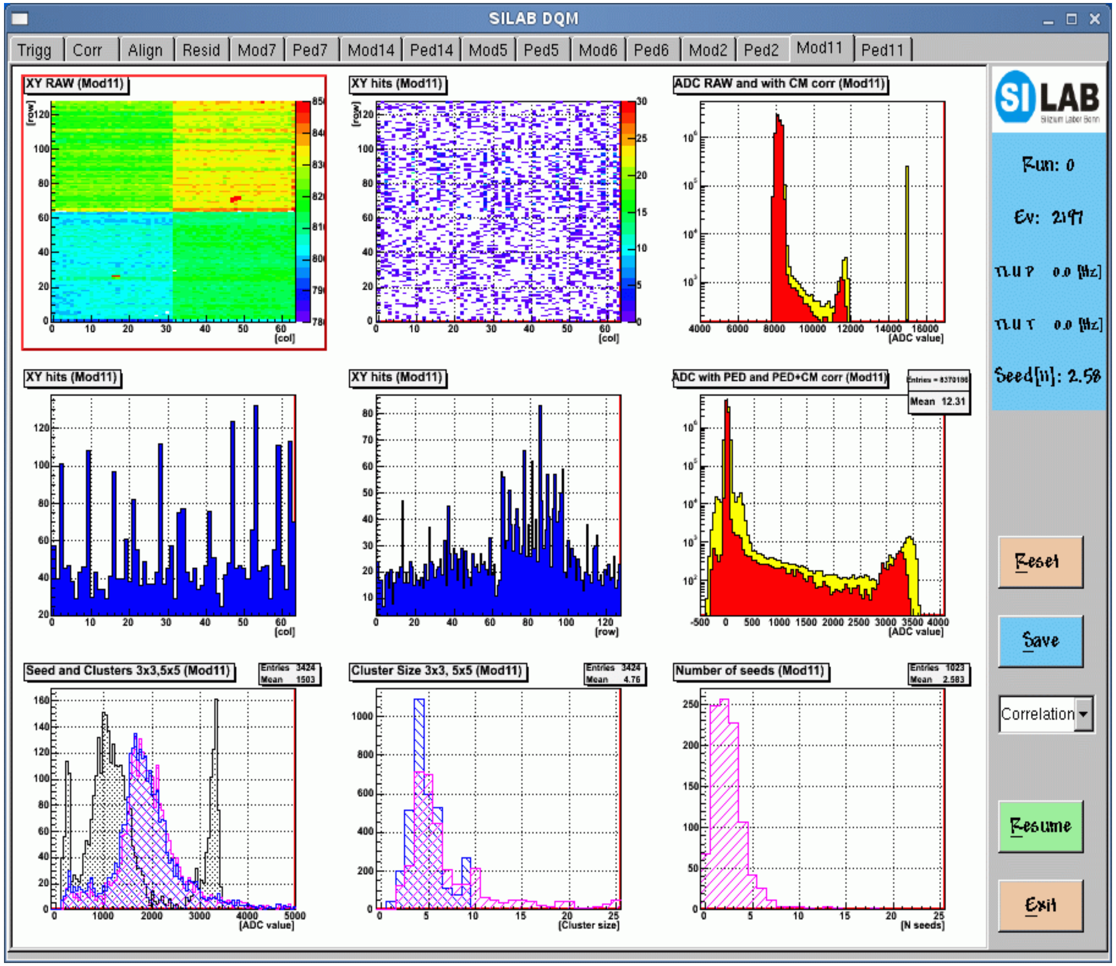
- *DAQ is based on Linux network distributed client/server architecture which allows :*
  - share resources and tasks
  - easy scale the system
  - remote control and monitoring
  - easy integration of other detectors



- *DAQ uses USB 2.0 for data transfer from DEPFET R/O board to PC and TCP/IP to send data to Event Builder .*
- *The DAQ components are:*
  - a LINUX based USB driver for the DEPFET DAQ board
  - a USB readout client transferring data to an event builder via network;
  - an Event Builder assembling complete events and storing in a shared memory buffer;
  - an event server send complete event to consumers (file writer, DQM, upper level DAQ, histogram server);
  - online Data Quality Monitoring (DQM) package based on ROOT.
- *Run control server can accept commands from different clients:*
  - Command line interface via Telnet
  - TCL/TK or Root GUI
  - Another program with TCP connection to Run Control

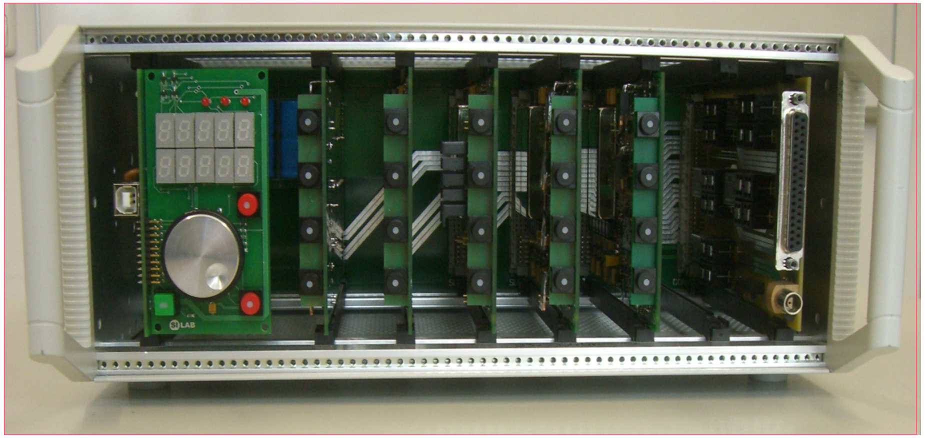
Data Quality Monitor

- *Network Data Acquisition system allows to run powerful Data Quality Monitor on dedicated PC in real time*
- *DQM is based on ROOT :*
  - includes various data access methods : file, shared memory, network
  - online data processing – pedestal and common mode calculation, cluster reconstruction and simple tracking.
  - can also act as network histogram server
- *advanced DQM functionality allows to find most of DAQ and DEPFET matrix problems during the run*
- *WEB interface for remote DQM*



Power Supplies

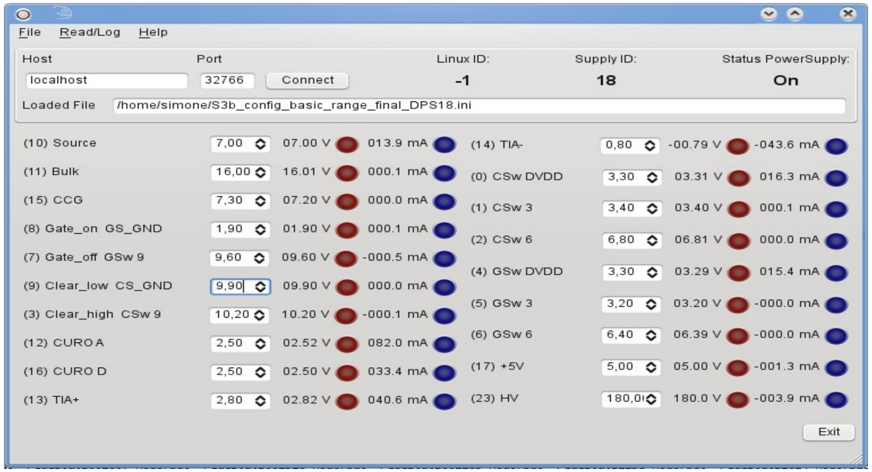
- *Up to 20 supply voltages are needed for operating a DEPFET system*
- *Special multi channel power supplies have been built to conveniently provide all voltages*
- *Computer controlled power supplies houses in small (15" case) :*
  - one supply per DEPFET module
  - safe power on sequence, (μC controlled)
  - easy voltage and current monitoring
  - remote access to voltage settings :
    - DUT voltage scans



Operation voltages of a DEPFET matrix with respect to source (0V)

	Collection	Read	Clear
V^*_{Gate}	$3V$	$-2V$	$-2V$
V^*_{Clear}	$2V$	$2V$	$15V$
V^{**}_{Drain}	$-5V$		
$V_{ClearGate}$	$-2V$		
V_{Bulk}	$10V$		
V^{***}_{Back}	$-10V \ldots -50V$		

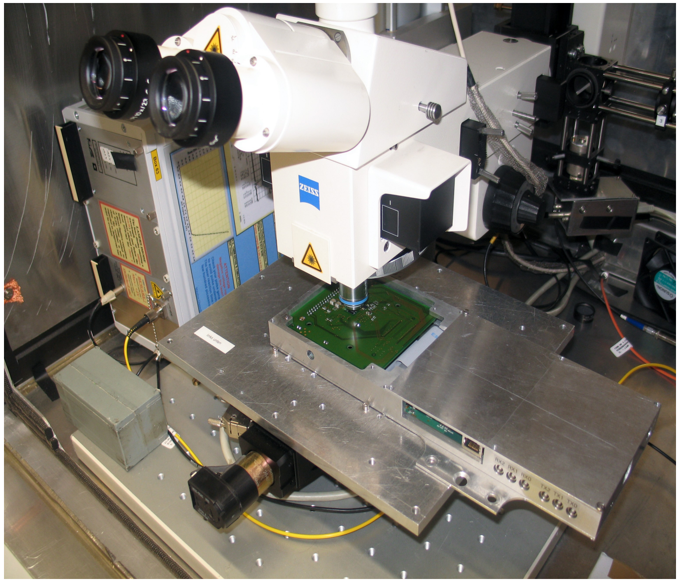
- $*$ control lines (transferred via Switcher)
- $**$ provided by readout input stage
- $***$ depending on final detector thickness and contact mode

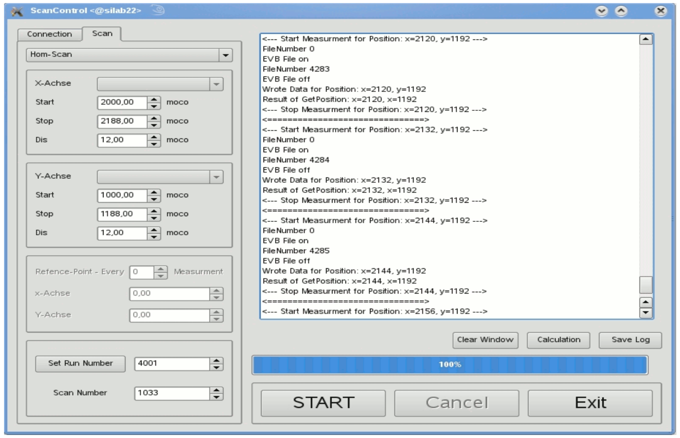


Laser Measurements in LAB

- *Laser tests are done in order to study inhomogeneity of the matrix response using laser systems with different wavelengths:*
  - 682 nm, 810 nm and 1055 nm.

- *The laser spot is focused on the matrix backplane with spot sizes which vary from 2.5 µm to 5 µm.*
- *The DEPFET module is mounted on a motor-controlled xy-stage with steps of the order of 1 µm, allowing a full automatic scan of the matrix surface*
- *Scanning software controls a motor table, laser and a data acquisition*

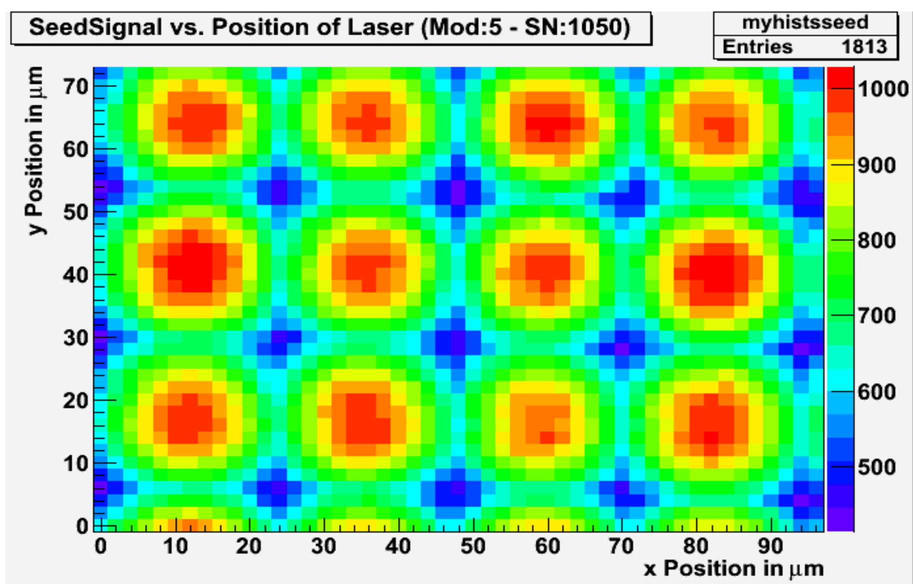




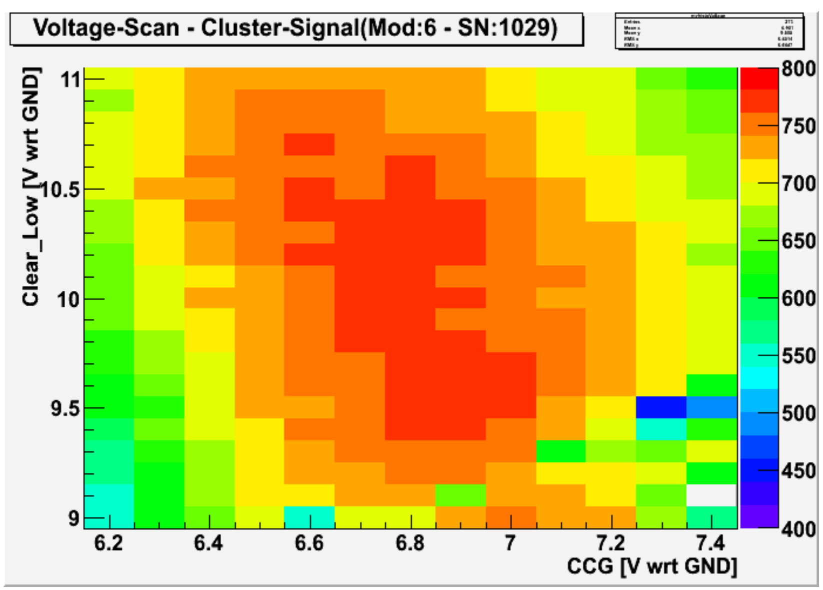
Laser measurements

- *In-pixel structure of DEPFET can be resolved*
- *Pixel size of a DEPFET sensor:*
  - 24x24 µm
- *Figure shows an example of the variations of the pixel seed signal across the matrix.*
- *Charge is shared in area of 3x3 pixels*
  - In seed pixel we have about half of total charge

- *Response of DEPFET sensor is mainly depending on three voltages:*
  - Clear High
  - Clear Low
  - Common Clear Gare (CCG)
- *Automatic Scan of these voltages is used to define optimal parameters of the module.*

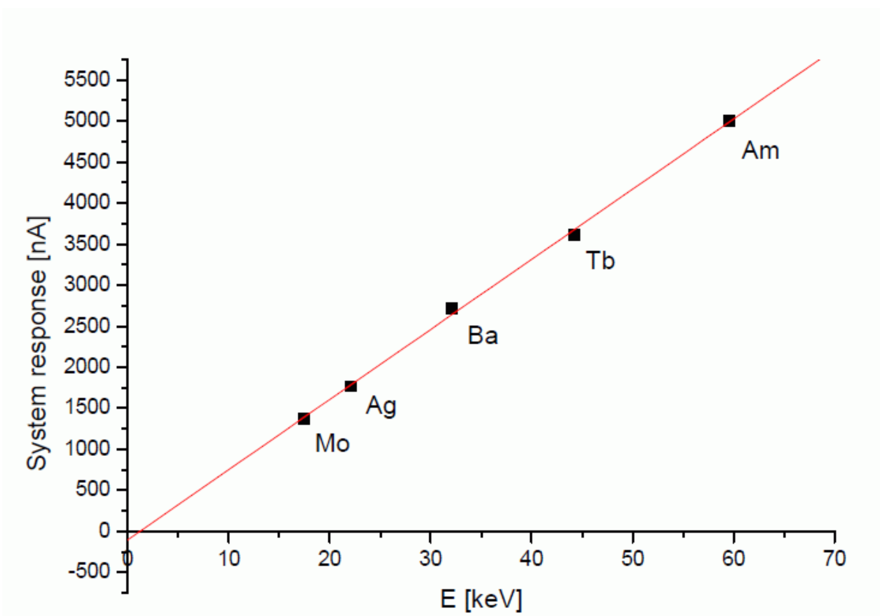


Step size: 2µm

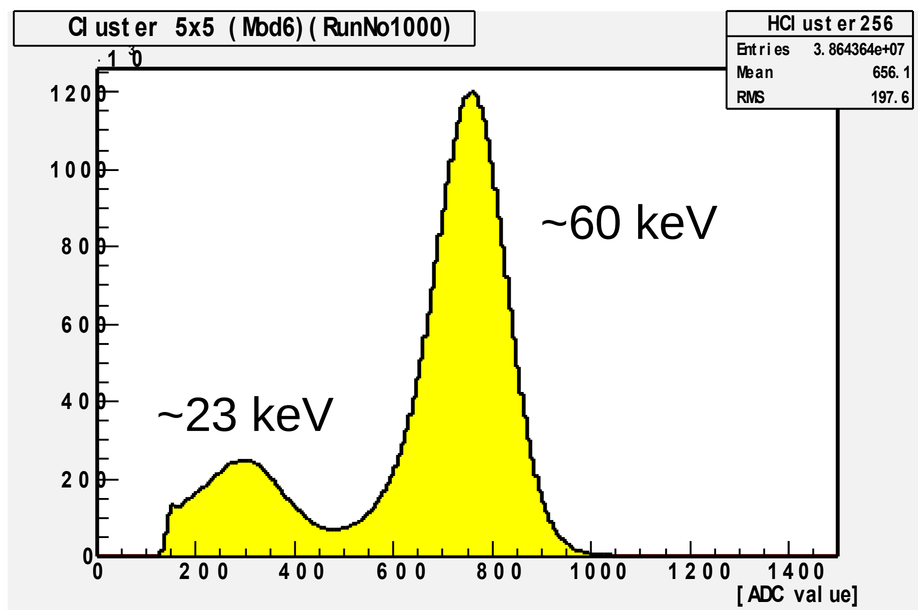


Tests with radioactive sources

- *Internal amplification of DEPFET -* G_q *defined as:*
  - $G_q = \Delta I_d / e^-$
- *For an absolute measurement of the gain* G_q*: spectra of radioactive sources are measured*
- *Measurements are usually performed using sources:* ^{55}Fe, ^{109}Cd, ^{133}Ba *and* ^{241}Am
- *Prototypes with the standard channel geometry have a* G_q *of about* **400 pA/e⁻**
- *DEPFETs with a scaled channel geometry show even better results* G_q **= 650 pA/e⁻.**

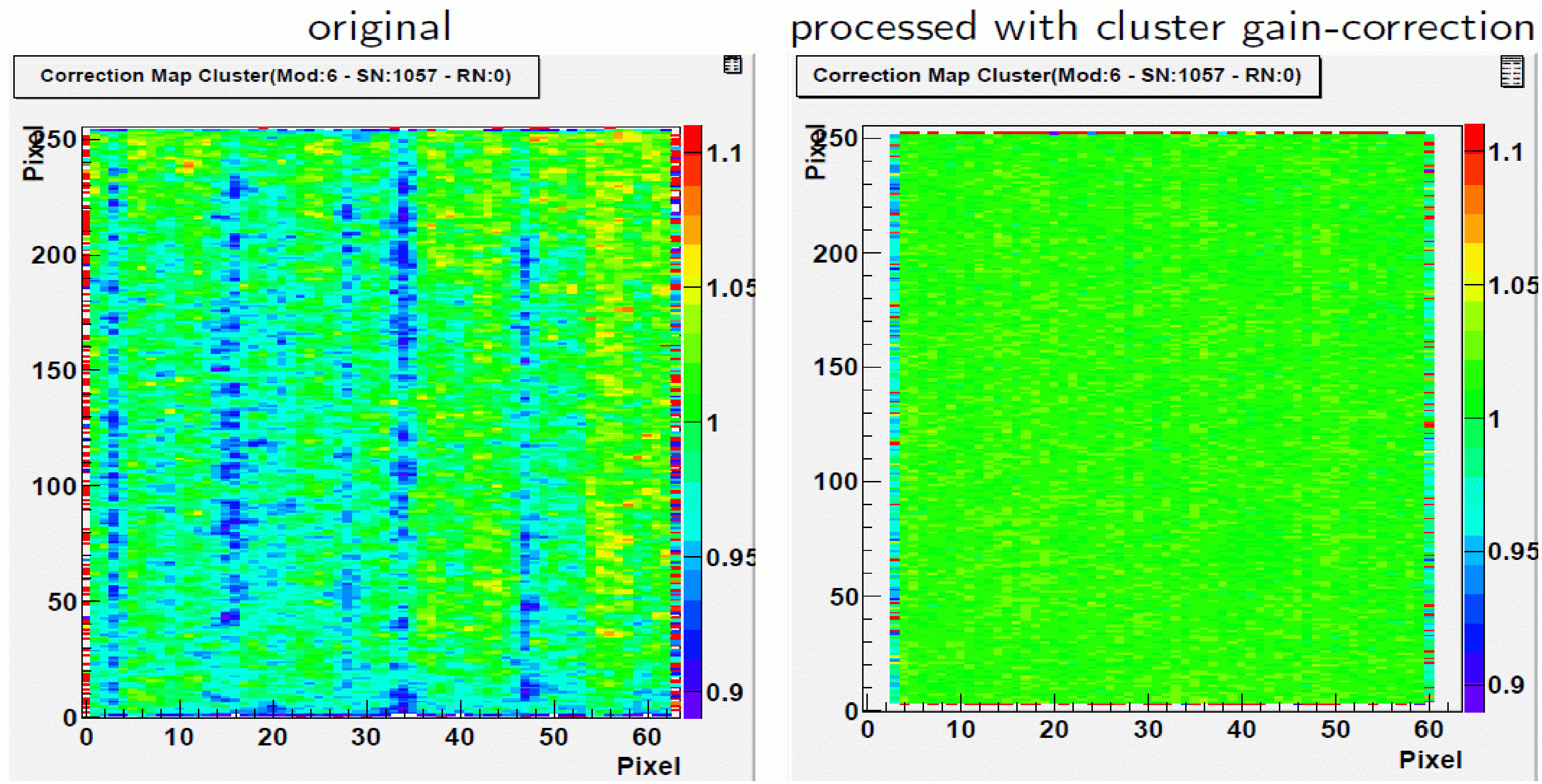


Energy spectrum of ^{241}Am



Matrix homogeneity measurements

- *The uniformity of the response over the DEPFET sensor has been measured.*
- *A spread of 5 % is observed when comparing the response of the over 16000 pixels of a sensor.*
- *This effect does not affect the spatial resolution significantly.*
- *Also it is possible to correct the difference in pixels gain.*



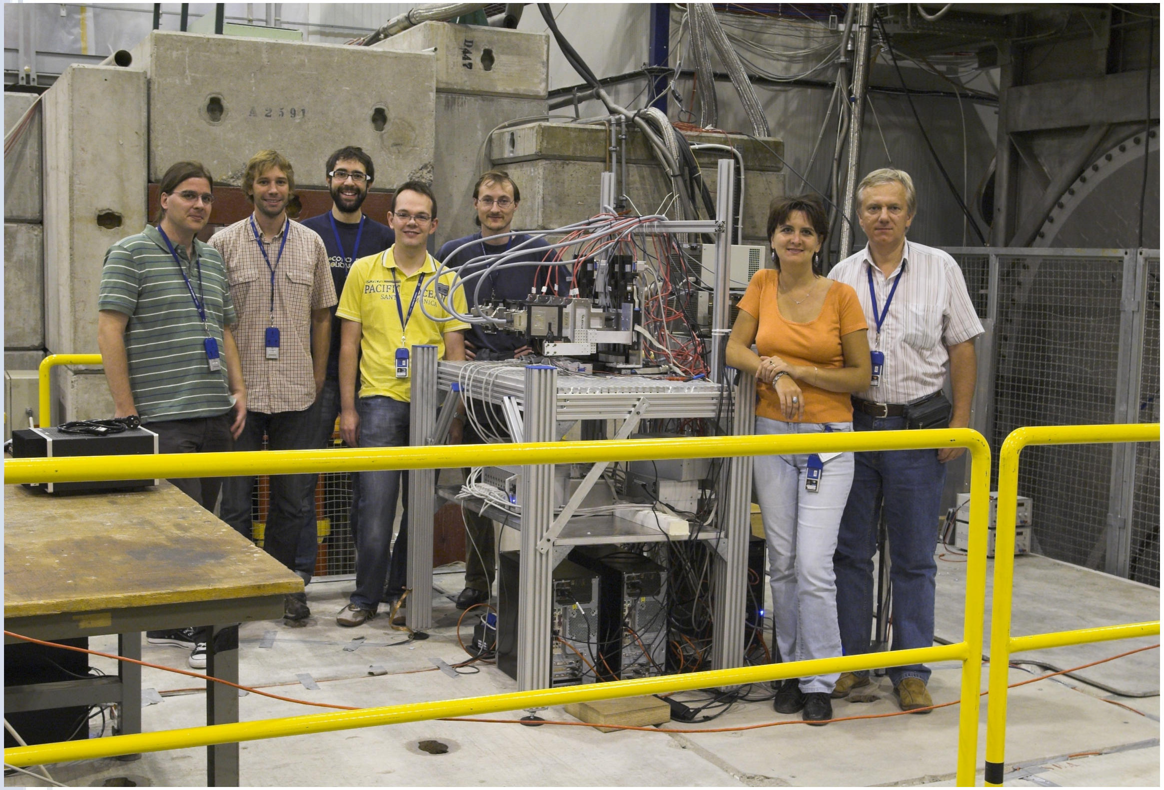
Test beam infrastructure

- *Beam tests of DEPFET prototypes form an important complement to the laboratory test procedures*
- *Their main aim is to characterize the response of DEPFET prototypes to minimum ionizing particles, and to establish the spatial resolution of the devices.*
- *Since 2005, DEPFET prototypes have been submitted to multiple beam tests in a 6 GeV electron beams at DESY, 24 GeV proton beams at the CERN PS and 120 GeV pion beams at the CERN SPS.*
- *Sophisticated beam test infrastructure has been developed :*
  - Mechanics:
    - support table for installation of DEPFET telescope system
    - X-Y motor stages with remote control, for alignment of DEPFET modules
  - Trigger includes:
    - scintillation counters in coincidence
    - Trigger Logic Unit (TLU) for synchronization readout system
  - Readout electronics
  - DEPFET matrix power supply
  - Data Acquisition system (DAQ)
    - Including PCs, network hardware and
  - Data quality monitor (DQM)

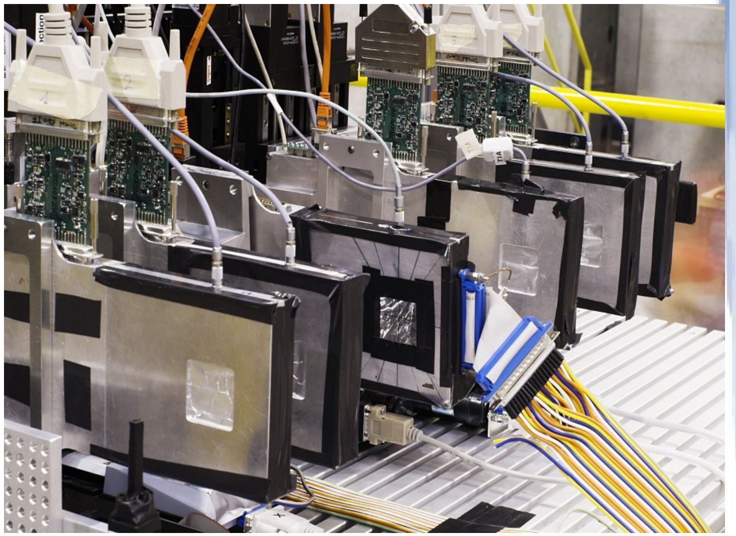
DEPFET Test Beam

- *Jul-Aug 2008, August 2009*
- *CERN SPS H6 beam line*
- *120 GeV pions*

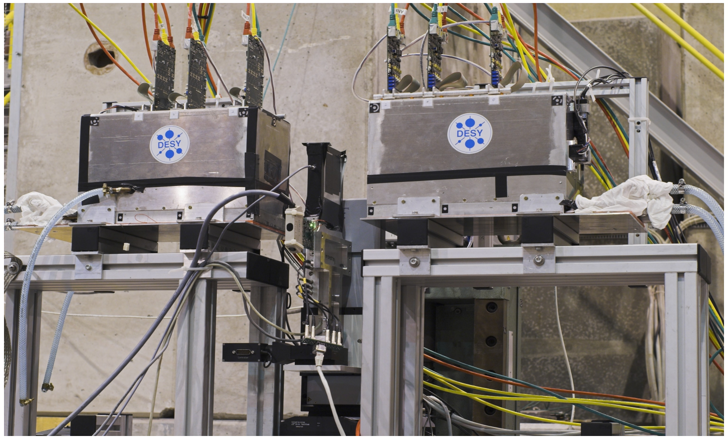
Test beam crew also important part of tests



DEPFET Telescope

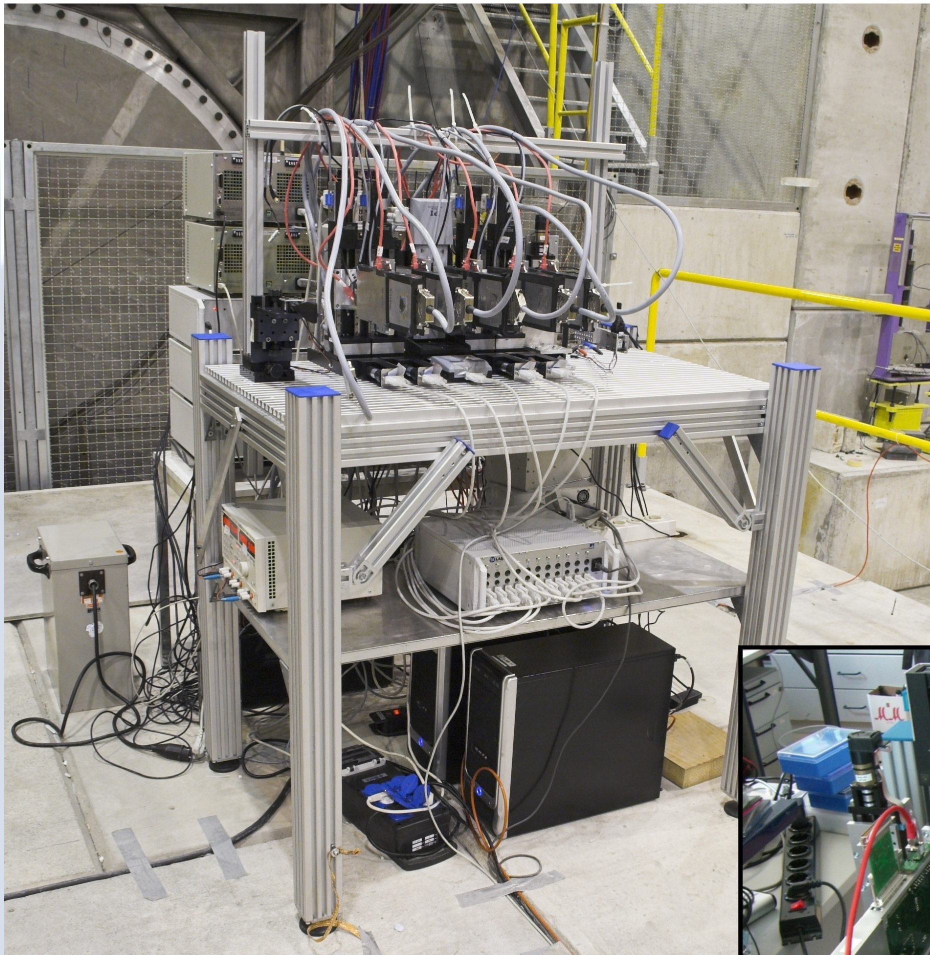


EUDET Telescope + DEPFET as DUT

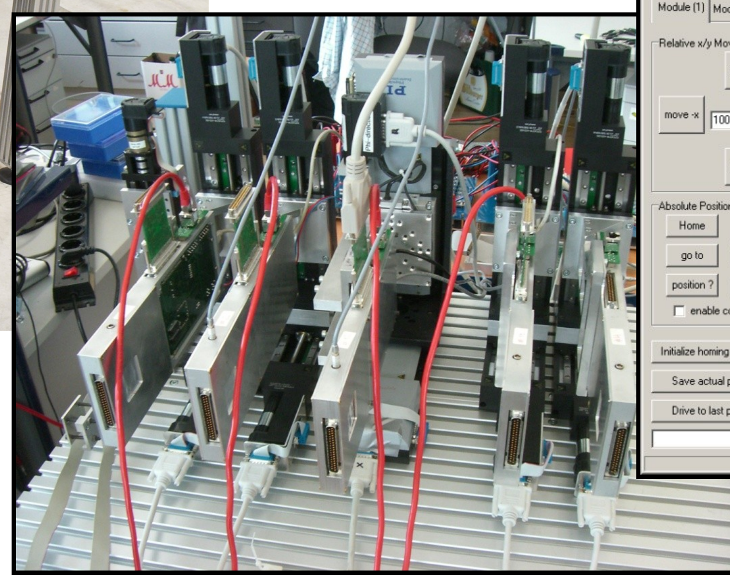


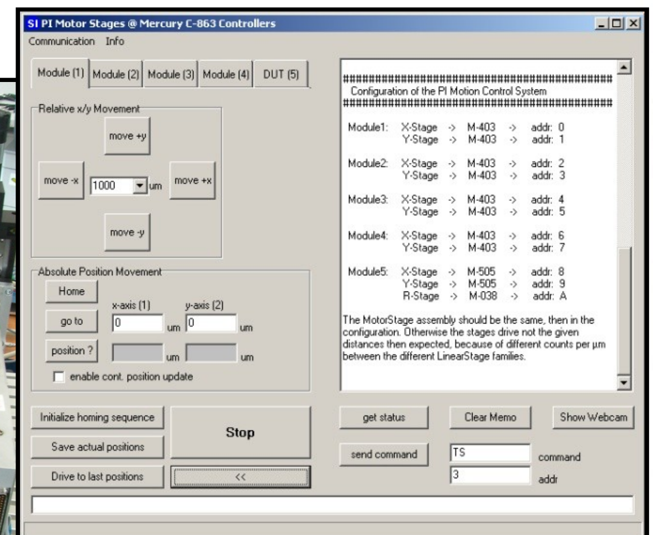
Mechanics

- *Telescope positioning system:*
  - Mechanics
    - moving range: 100/150mm, 90° rotation for DUT
    - positioning accuracy 15μm / 2μm (DUT)
  - Controllers
  - Positioning software

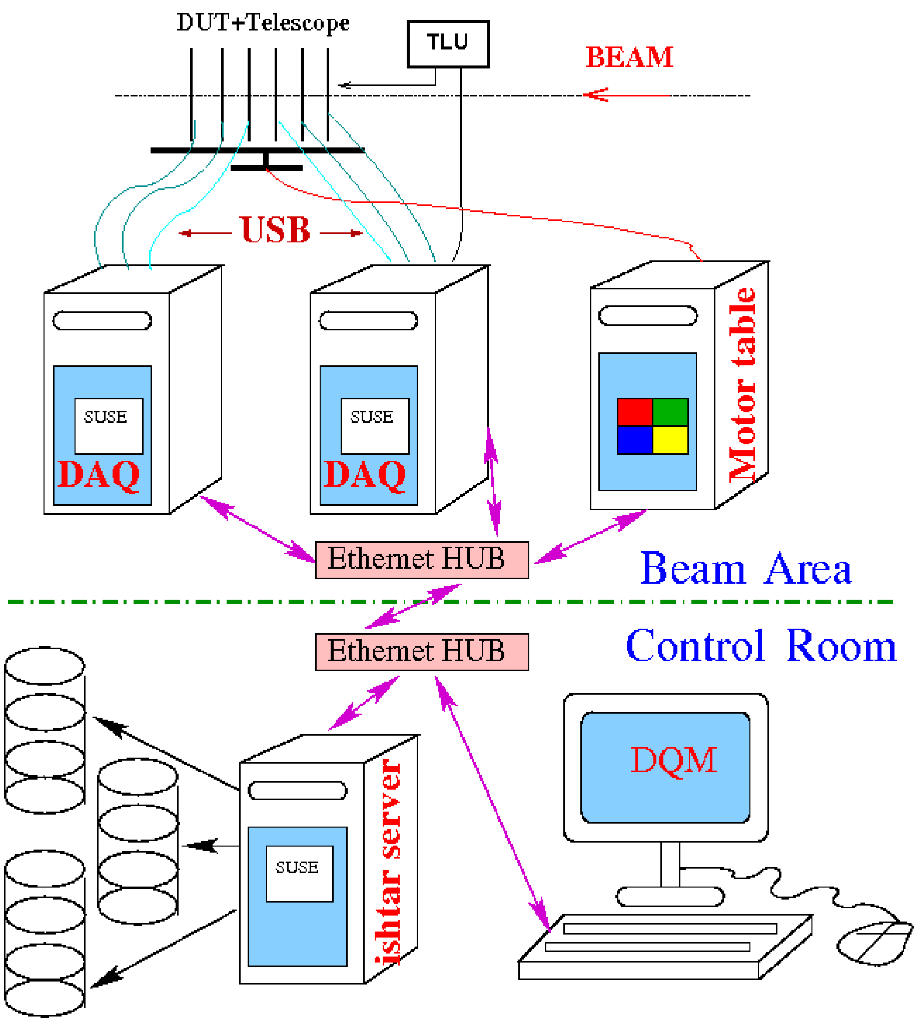


mounting table (1600x625x1050 mm)



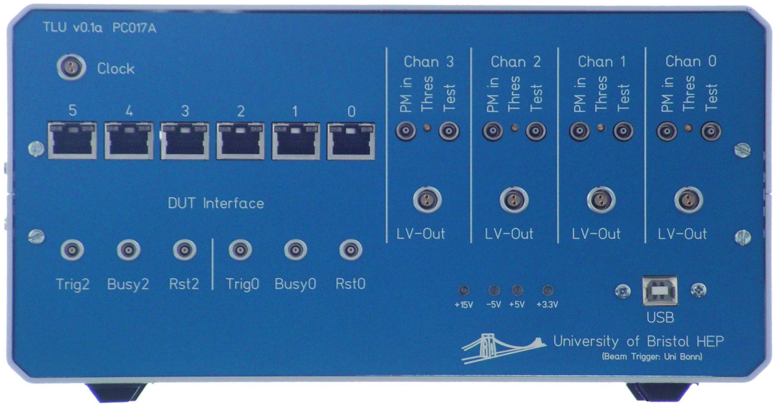


Test Beam setup for CERN 2009



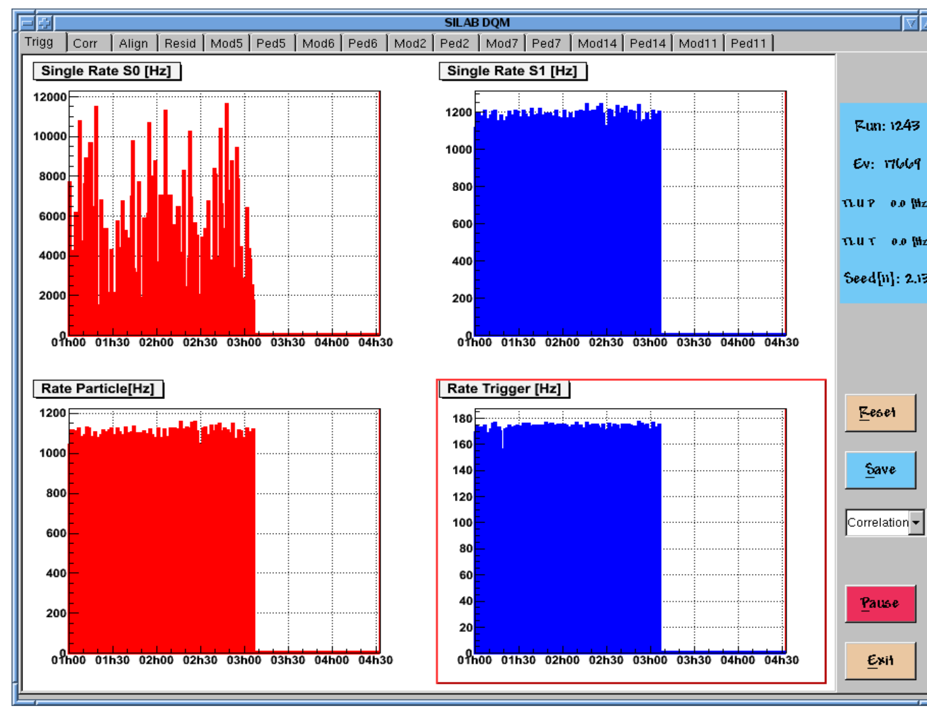
- *Test Beam Area :*
  - table with DEPFET telescope consisting of 6 modules, mounted on X-Y motor stages
  - 2 readout PC with 3 DEPFET modules per PC, connected via USB2.0 in the test beam area in distance of max. 4 meters from the modules.
  - Windows PC to control 6 X-Y motor stages, with USB2.0 connection to controller.
  - Trigger Logic Unit (TLU) connected to one of readout PC via USB2.0
  - all PC are connected to 1GB ethernet HUB
- *Control Room :*
  - one DAQ server – rack mounted server PC : Intel S5000, 8 CPU, 4GB memory, hot swap SATA RAID with 3 TByte disk space – total 6 disks.
  - working PC : Run Control, DQM, etc....
  - all PC also connected to local ethernet HUB
  - both HUBs are connected by ethernet cable, from test beam area to control room

Trigger and Events Rate



- *A dedicated Trigger Logic Unit (TLU) accepts signals from the scintillators or external trigger and generates a signal to trigger the system.*
- *Each trigger carries a unique number and time stamp.*

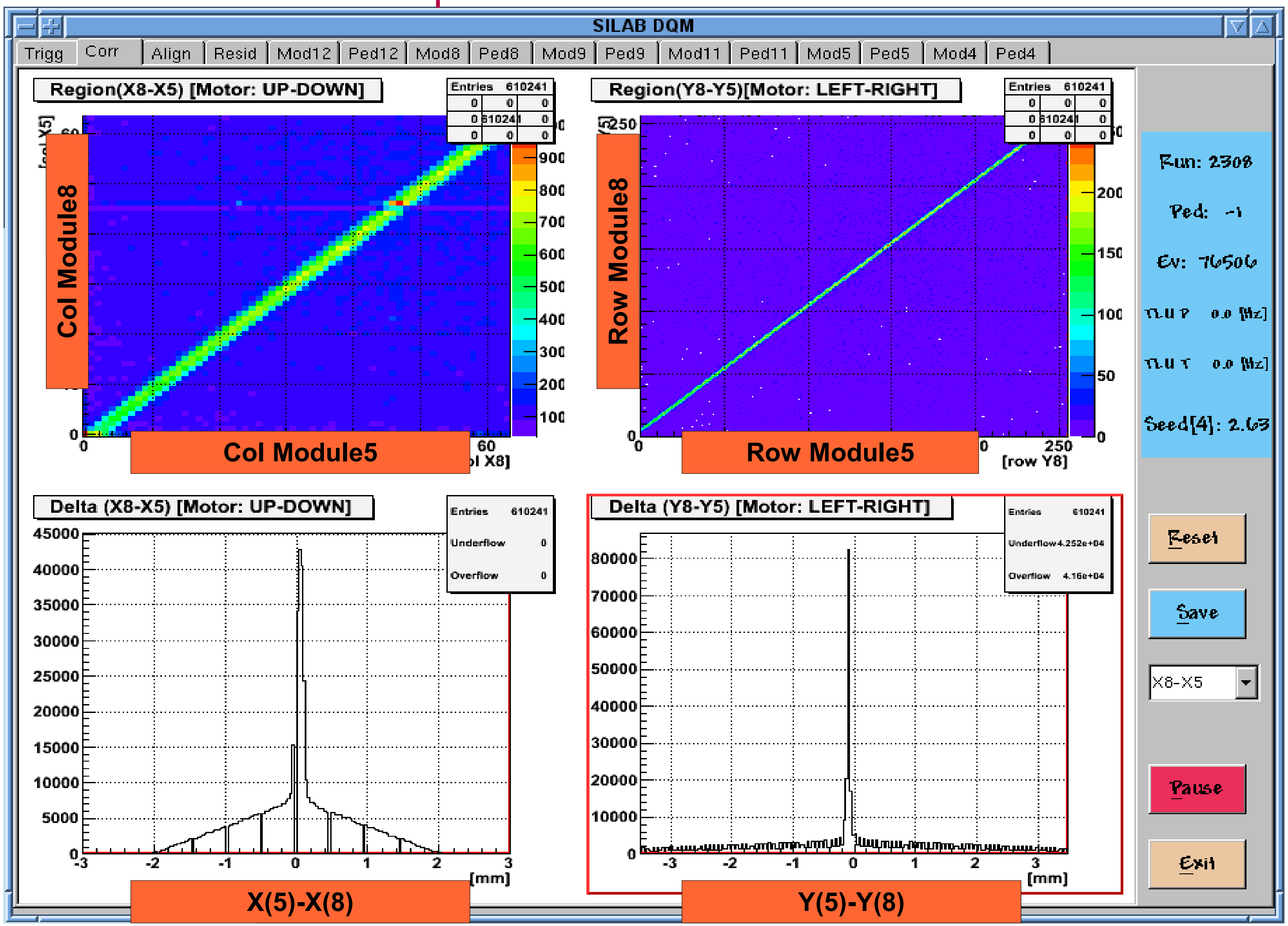
- *H6 line with 120 GeV pions*
- *Coincidence rate of 2 scintillators is about 1000 Hz*
- *DAQ with slow readout sequence (readout full matrix 64x128) accepts 180-220 Hz depending on number of readout PCs.*
- *Data volume rate for 6 modules is about 20 GB / hour*
- *One disk of 500GB is filled in 1-2 days*
- *Hot swapping RAID system allows to change the disks without stopping taking data*



Initial alignment of TB setup

- *Online Monitor also is used for alignment of all 6 modules on the beam line:*
  - 6 sensors with size of 2x3 mm and distance between modules about 20 cm

Correlation plots for two modules: Mod8 & Mod5



Analysis

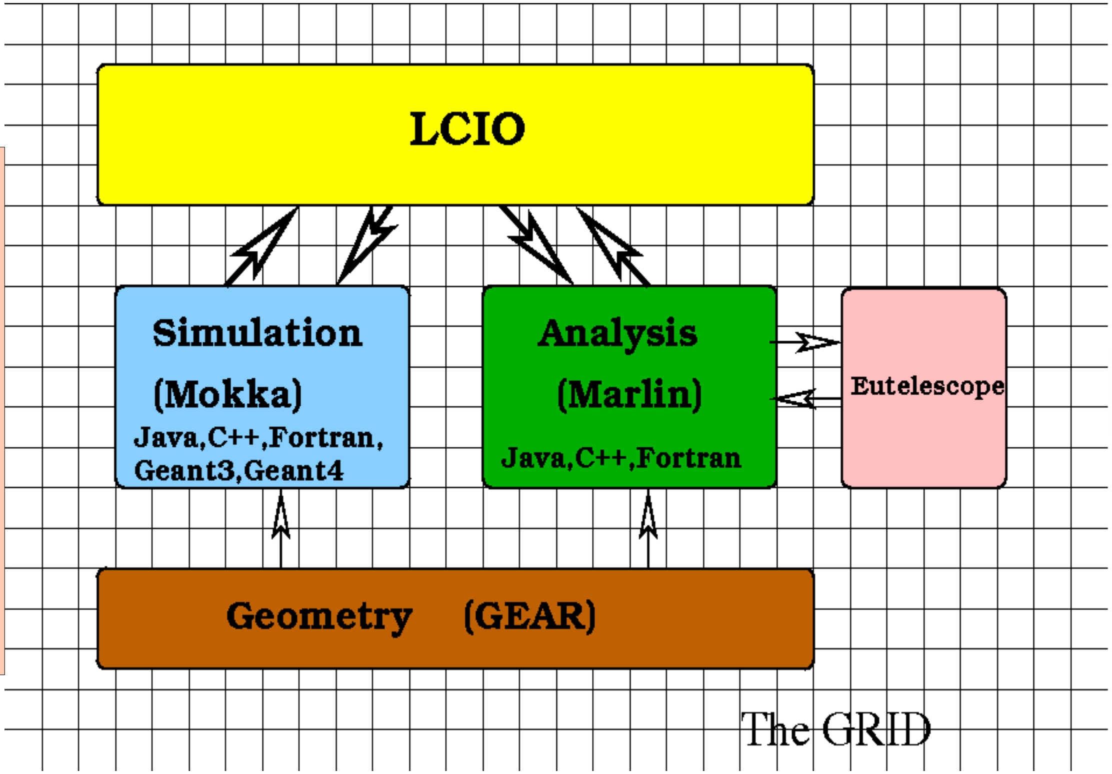
- *Data analysis has been carried out and cross-checked by several groups, each using different tools:*
  - Framework (ILC/EUTelescope vs. ROOT)
  - Alignment (Millepede vs. alignment)
- *The analysis groups collectively cover a wide range of specialized analysis tasks (from charge collection homogeneity analyses to studies of response variations across detector matrices to calculation of detector resolutions*
- *Detector (spatial) resolutions (Prague)*
  - calculated from fit residuals by "subtracting" multiple scattering contribution using the statistical models of particle track and multiple scattering.
  - Useful tool to study and optimize detector properties (hit reconstruction, homogeneity of response etc.)
- *Simulation studies and digitization:*
  - For validation of analysis
  - For studies of detector designs for HEP experiments (Belle II, ILC)

ILC data analysis software

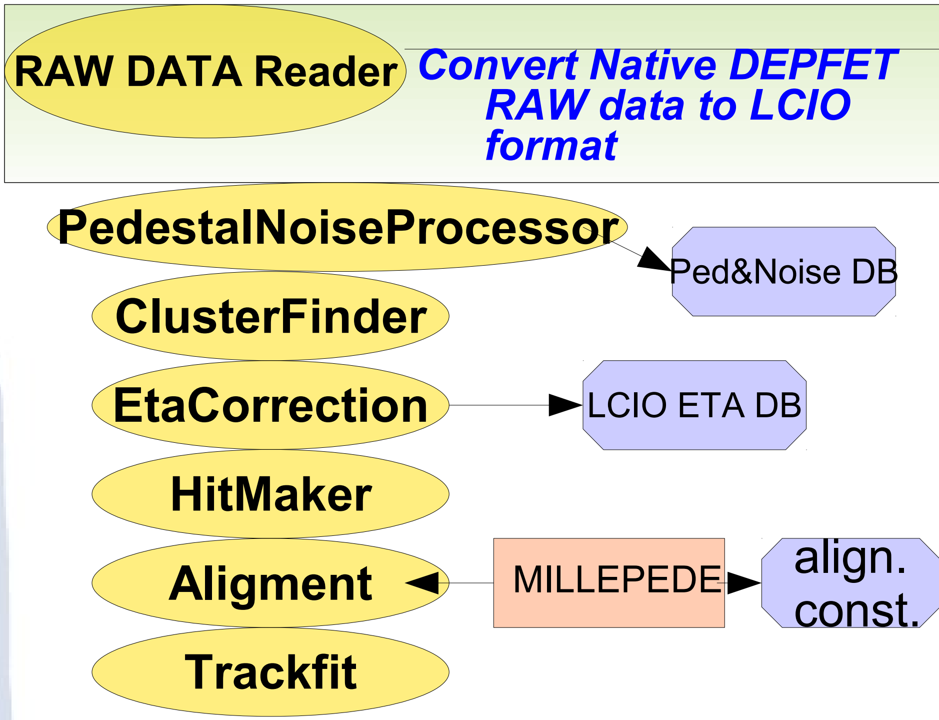
- *Data analysis is based on ILC framework software for tracking and alignment with modification for DEPFET specifics mainly in part*
  - of cluster reconstruction
  - common mode correction.

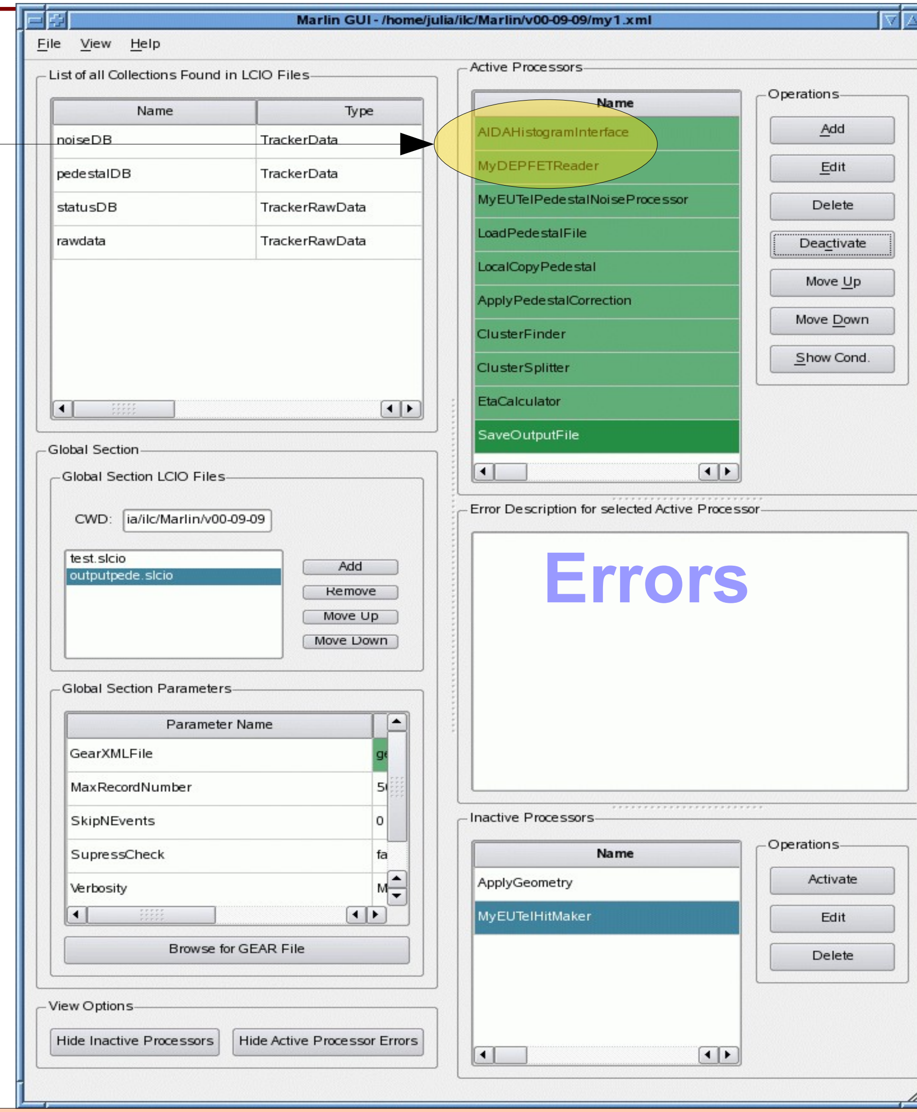
- **LCIO (LiniarCollider I/O): persistency framework and data model**
- **MARLIN: C++ application framework**
- **GEAR: geometry description**
- **RAIDA: interface to ROOT**

- **Advantages:**
  - **use standard analysis tools and reconstruction software**
  - **space for own development**
  - **integrate with GRID for data management and processing**



ILC/EUTelescope software





- LCIO (LiniarCollider I/O): persistency framework and data model that has been adopted as a standard by the international ILC community.
- MARLIN:C++ application framework
- GEAR: geometry description
- RAIDA: interface to ROOT
- Eutelescope: applications for TestBeam

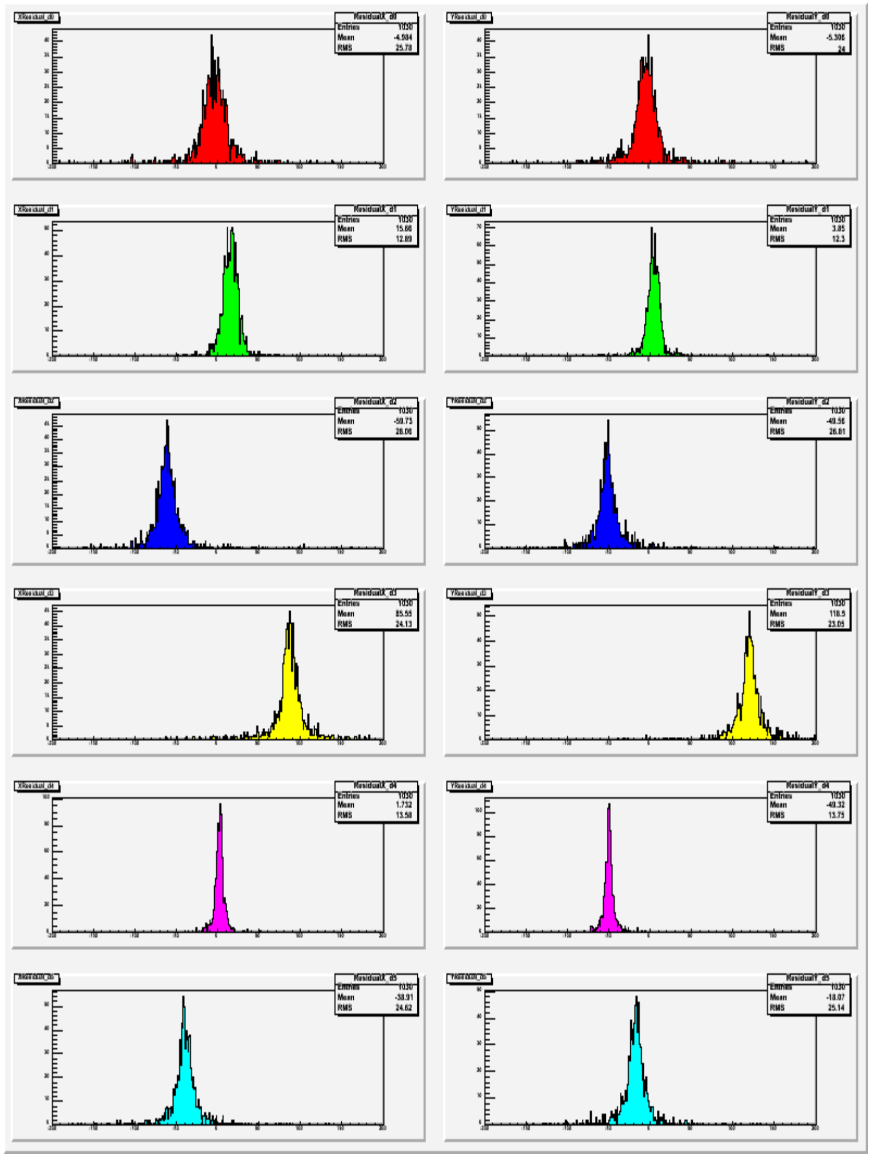
Advantages of the ILC software:

- standard analysis tools and reconstruction software
- space for own development
- integrated with GRID for data management and processing

Milepede II alignment

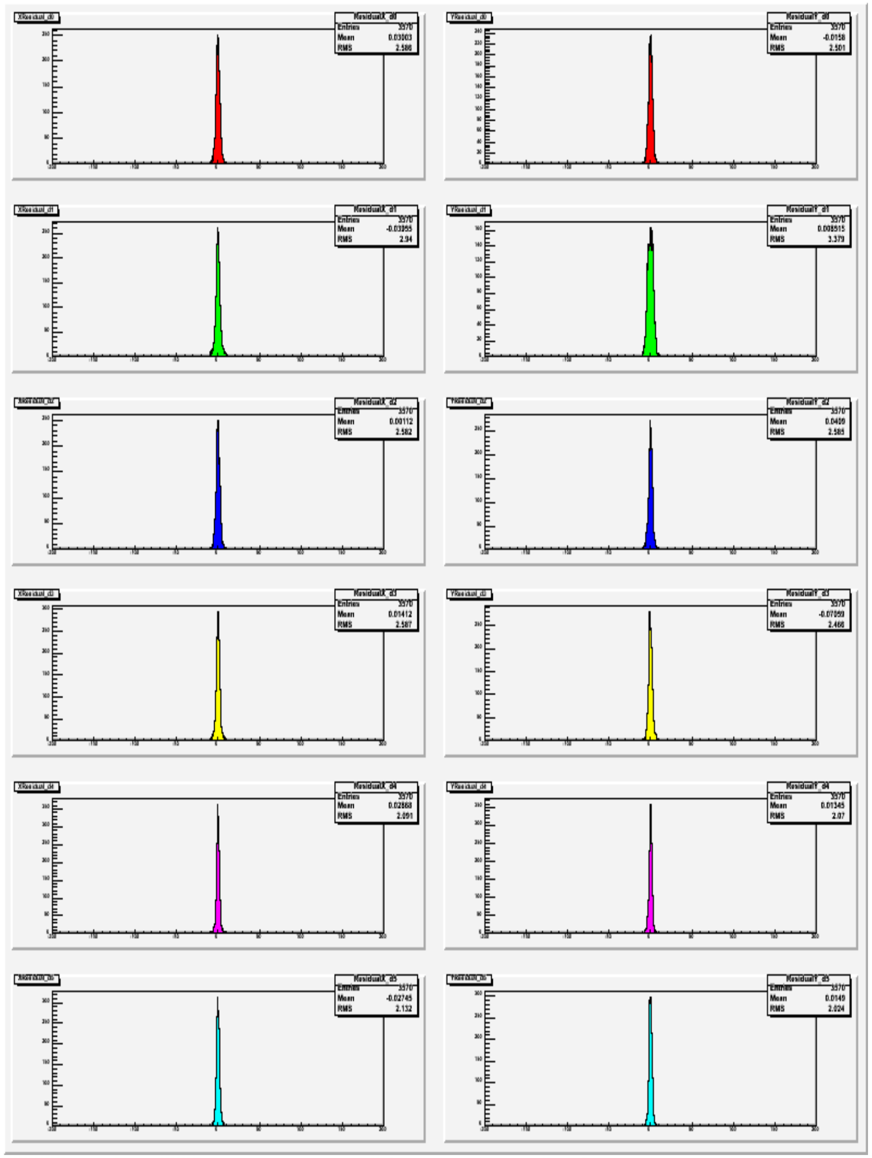
Before alignment

(track-hitX) *(track-hitY)*



After alignment

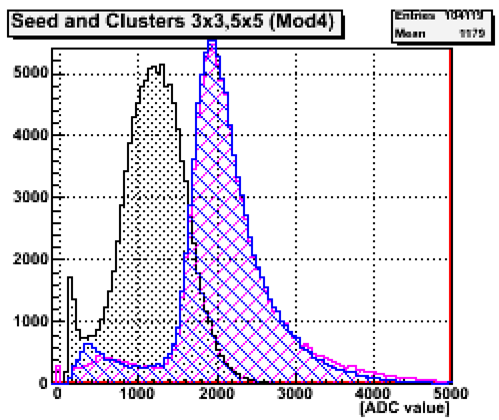
(track -hitX) *(track-hitY)*



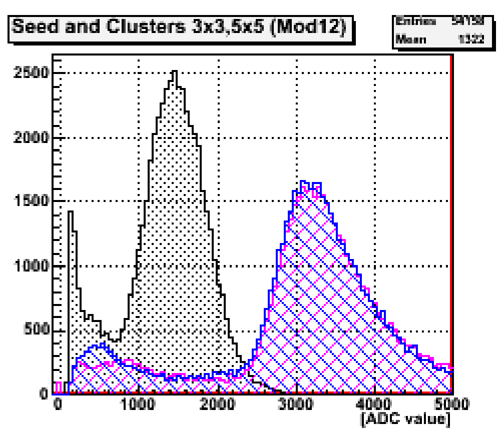
Cluster signal and noise

- *The most probable signal ranges from 1600 to over 3000 ADU in different sensor designs.*

Telescope Module COCGLB: S/N ~130

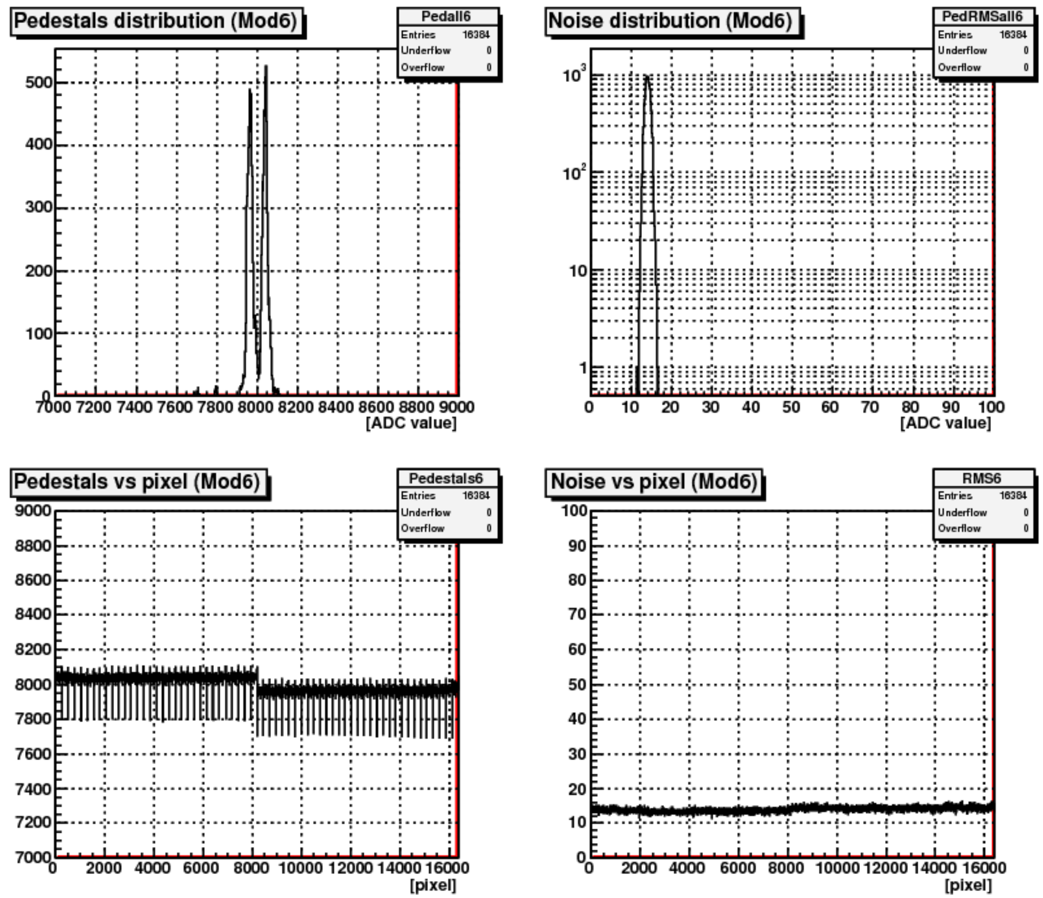


Module COCG VS (20x20 µm) : S/N ~220



- *The noise level in these devices is approximately 13 to 14 ADU.*
  - signal-to-noise ratio of well over 100.
  - S/N for COCG VS over 200

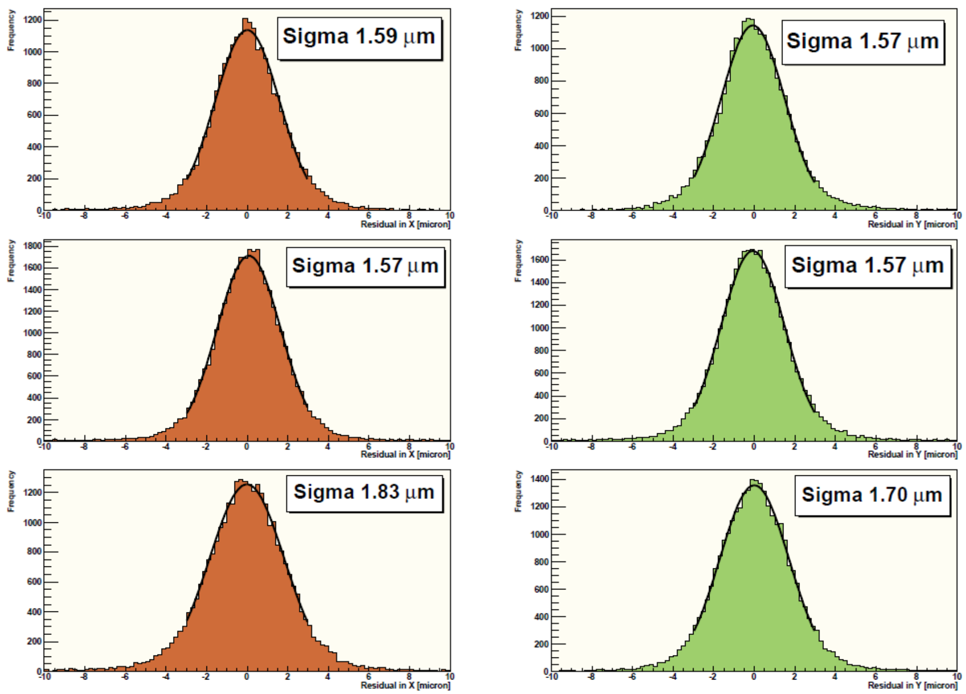
Pedestal and noise distributions



Preliminary TB 2009 analysis

Analysis of the DEPFET data at University of Göttingen , using ILC/EUDET software

Residuals X   Residuals Y



Residuals in x and y of H3.0.04, H3.0.07 and H3.0.01. Telescope and DUT hits reconstructed with eta px couple algorithm.

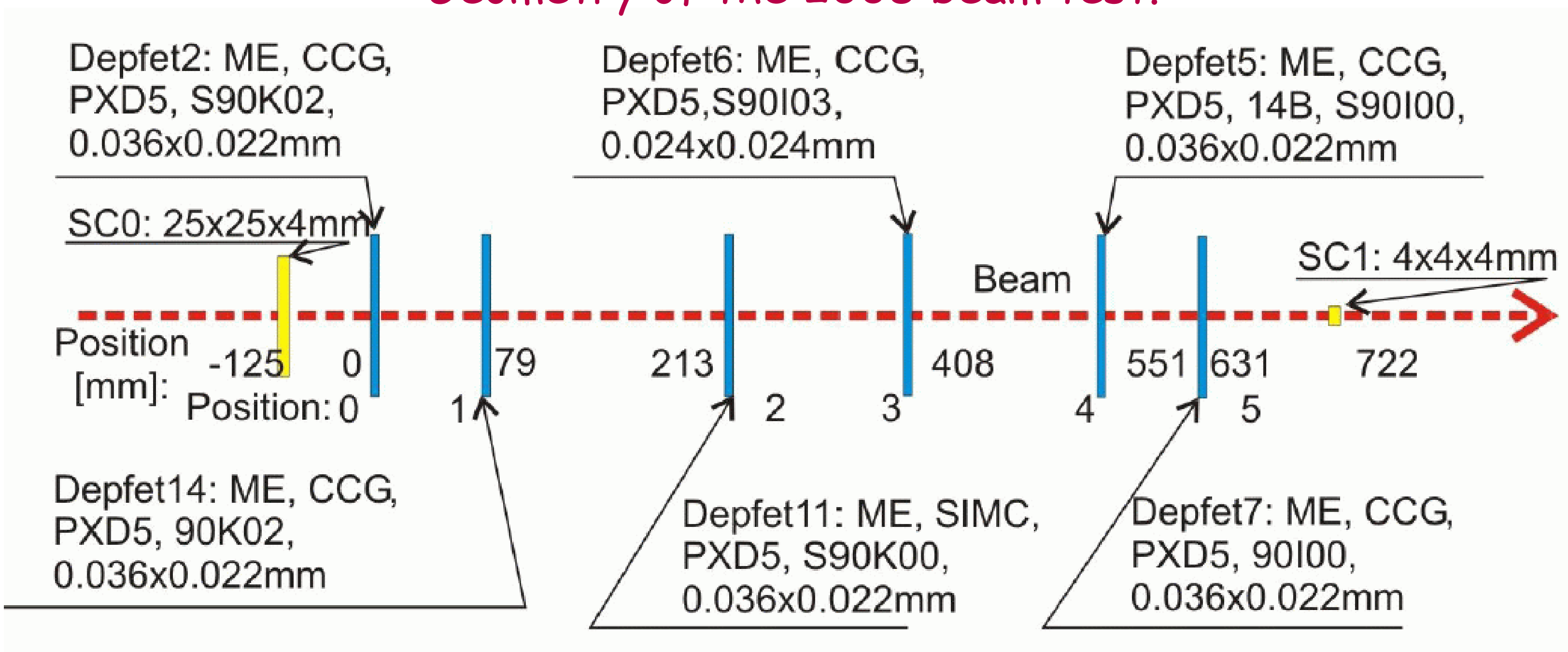
	FF3x3	FF3x3 NR2.6	FF5x5	FF5x5 NR2.6
Center of Gravity	2.13 / 1.85	2.16 / 1.85	2.10 / 1.82	2.13 / 1.83
η (CoG)	2.03 / 1.96	1.88 / 1.80	2.64 / 2.63	2.29 / 1.96
η (Column Couple)	1.73 / 1.66	1.73 / 1.66	1.70 / 1.64	1.70 / 1.64
η (Pixel Couple)	1.69 / 1.66	1.70 / 1.66	1.65 / 1.63	1.66 / 1.63

The matrix chart displays the residuals for x (red) and y (green) in dependence of the clustering procedure and the hit reconstruction algorithm in μm.

FF = Full Frame; NR2.6 = Noise Reject at 2.6 Sigma

Final TB 2008 resolution

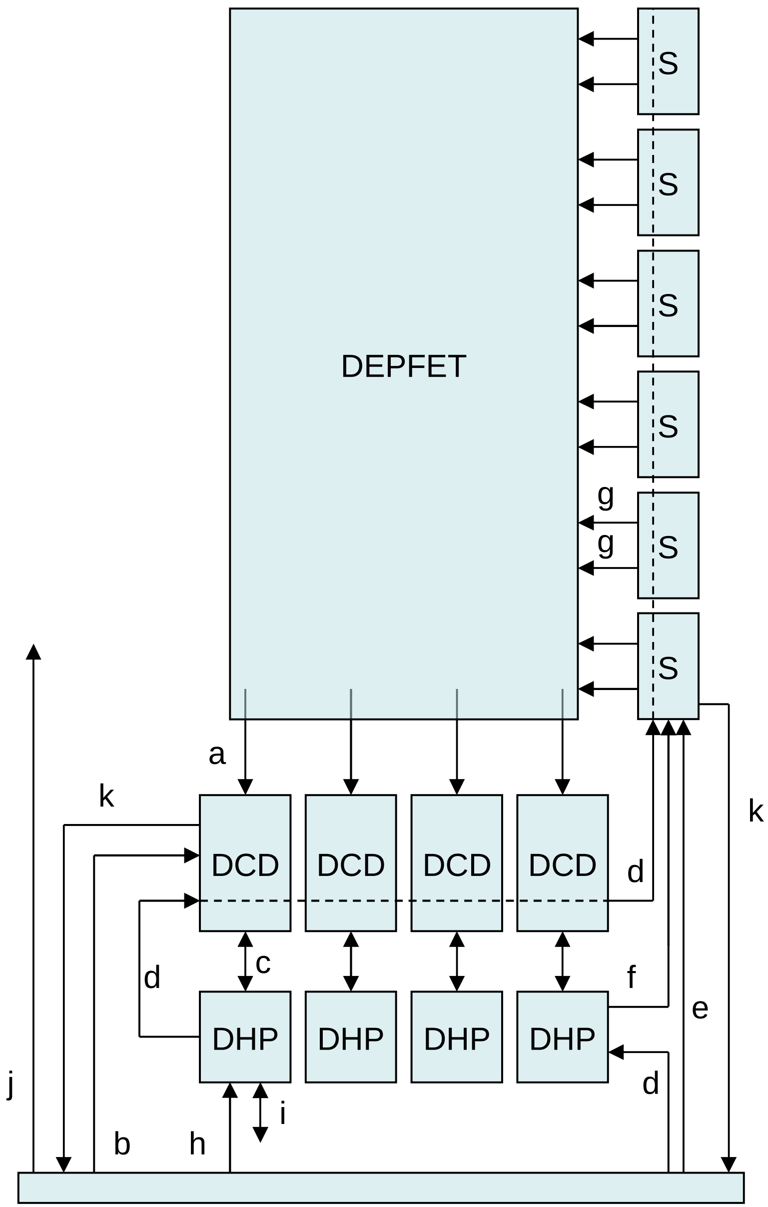
Geometry of the 2008 beam test.



Final residuals and resolutions from Prague analysis

Y resolution [μm]	Module 0 CCGME- -S90K02 32x24 μm	Module 1 CCGME- -90K02 32x24 μm	Module 2 SIMCME- -S90K00 32x24 μm	Module 3 CCGME- -S90I03 24x24 μm	Module 4 CCGME- -S90I00 32x24 μm	Module 5 CCGME- -90I00 32x24 μm
X residual [μm]	2.9	2.2	2.3	2.0	3.1	3.4
Y residual [μm]	2.3	1.7	1.7	1.7	2.2	2.6
X resolution [μm]	2.1	1.6	1.9	1.3	2.6	2.4
Y resolution [μm]	1.5	1.3	1.2	1.2	1.8	1.7

New Readout of DEPFET



a A(0:255)

b analog AVDD, AGND, AmpLow, RefIn (+4xrefCurr)

digital DVDD, DGND

c DCD->DHP DO(0:63), RefOut

DHP->DCD DI(0:15)

DCD->DHP CLK, SYNC_RES, STR

SYNCHR(0:1)

d JTAG5x

e HV AHI, ALO, BHI, BLO, SUB, Ref?

LV VDDD3.3, GNDD, VDDJTAG1.8

f CLK, SERIN, SEROUT STRGATE, STRCLR

g CLR(0:31), GATE(0:31)

h VDDDC_DHP, GNDD_DHP, VDDGB_DHP, VDD1.8_DHP,

i IO DHP

j S, CG, PC, GU, HV

k Monitor_DCD, MonA_SW, MonB_SW

Conclusion

- *A system for characterization of DEPFET matrices includes :*
  - Laser and radioactive sources setups at Laboratory
  - Test Beam setups (CERN, DESY)
    - Standalone DEPFET telescope
    - Integration with EUDET telescope on the hardware and software level
- *Data acquisition system is running stable and has shown good performance*
  - Operated 6 layers DEPFET telescope (trigger rate ~100 Hz, data rate ~20 GB/hour)
  - Collected ~ 20 millions events for analysis (~4TB raw data)
  - Flexibility: DEPFET DAQ has been successfully integrated to EUDET readout system
- *Analysis Software*
  - Several analysis tools from a different groups are available to cross check the results.
  - ILC/EUTelescope software is used as default for data analysis.
- *The spatial resolution in TB2008 for matrix with 24 × 24 μm² pixels is found to be:*

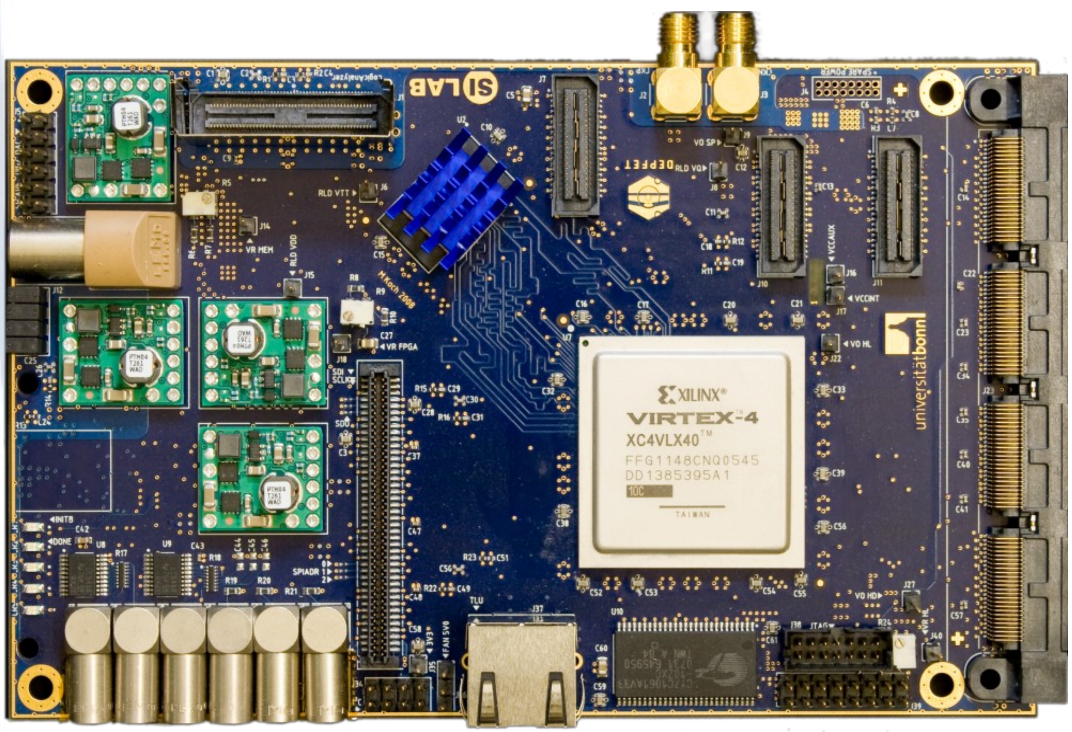
$$\sigma_x = 1.3 \pm 0.2\ \mu m, \quad \sigma_y = 1.2 \pm 0.1\ \mu m$$

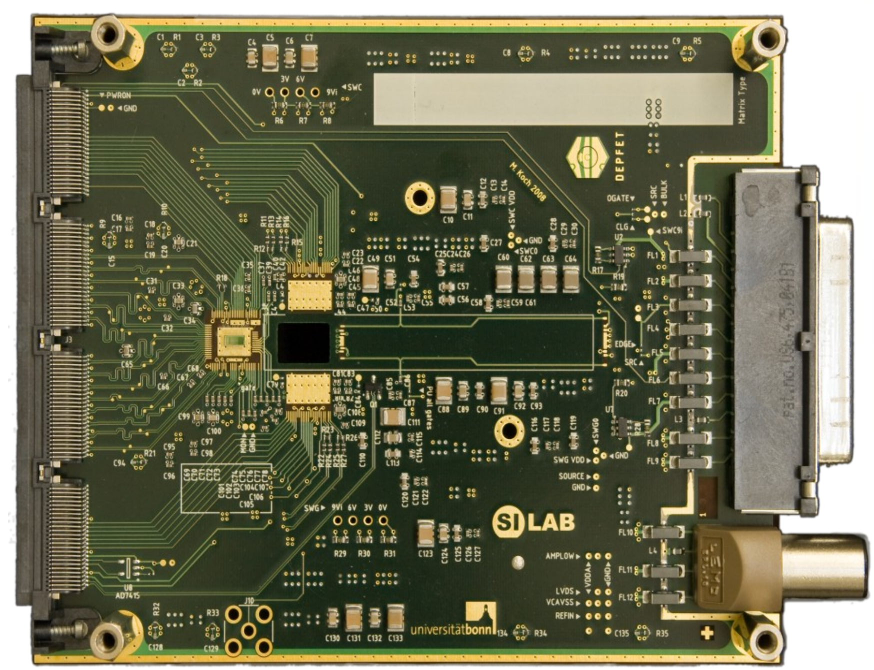
- *Signal to noise ratio for DEPFET telescope planes ~130, DUT module S/N ~220*
- *The future test system with DCD readout is also planned to use this environment*

Backup Slides

Prototype of the new R/O system

- *The new prototype of ReadOut system consists of 2 PCBs:*
  - Hybrid PCB - houses DEPFET, Steering and Readout chips
  - Readout PCB - FPGA, RAM, USB
- *prototype of DCD2 chip is available (reduced number of connections) and tested on slow readout system*
- *DAQ for the fast readout system is based on existing USB 2.0 interface*



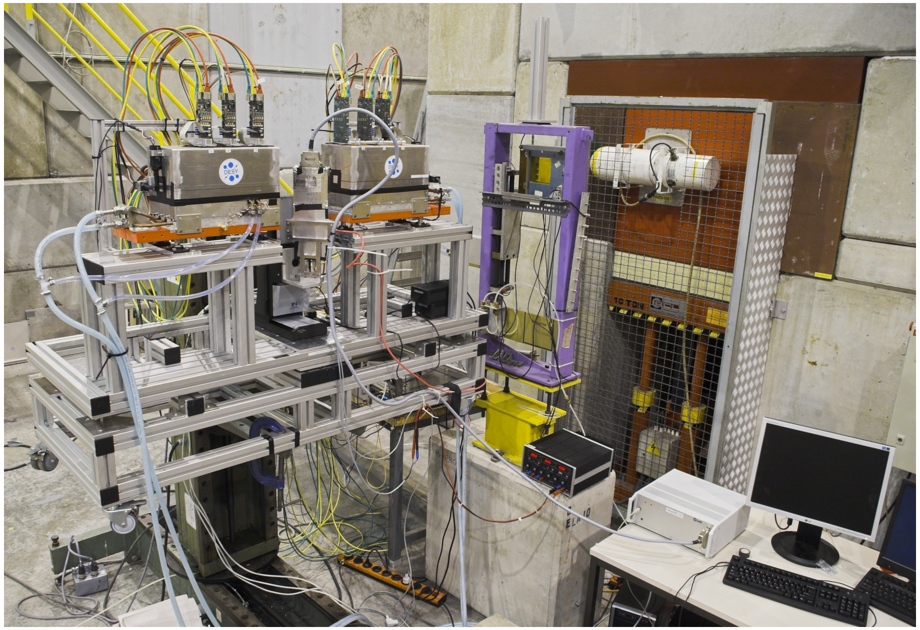


DEPFET with EUDET Telescope

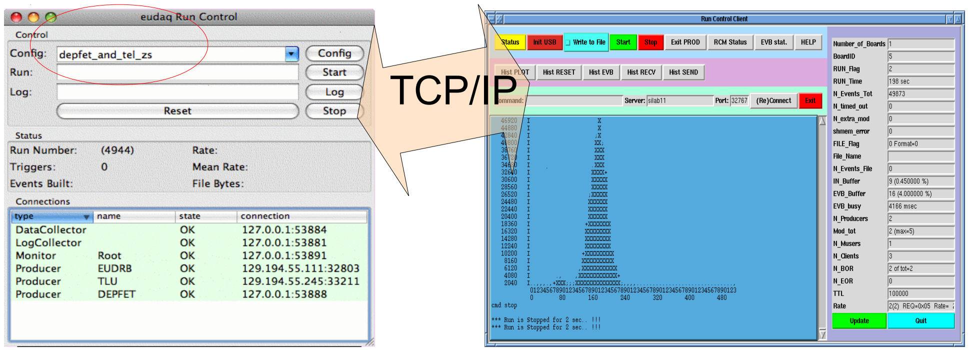
EUDET project is a program to develop the infrastructure, to facilitate the experimentation and to enable the analysis of data using shared equipment and common tools.

JRA1- test beam infrastructure (EUDET Telescope)

- *6 EUDET Modules MAPS - Monolithic active pixel sensors :*
  - 7.7x7.7 mm^2,
  - 256x256 pixels
  - pitch 30x30 μm^2
- *MVME6100 PowerPC computer with general purpose acquisition boards (EUDRB) inside the VME64x crate connected to 1GB ethernet HUB*
- *EUDET DAQ server on MAC PC , 1GB Ethernet*
- *Trigger Logic Unit (TLU)*
- *DEPFET DUT with Readout PC*
- *About 2 million events collected*

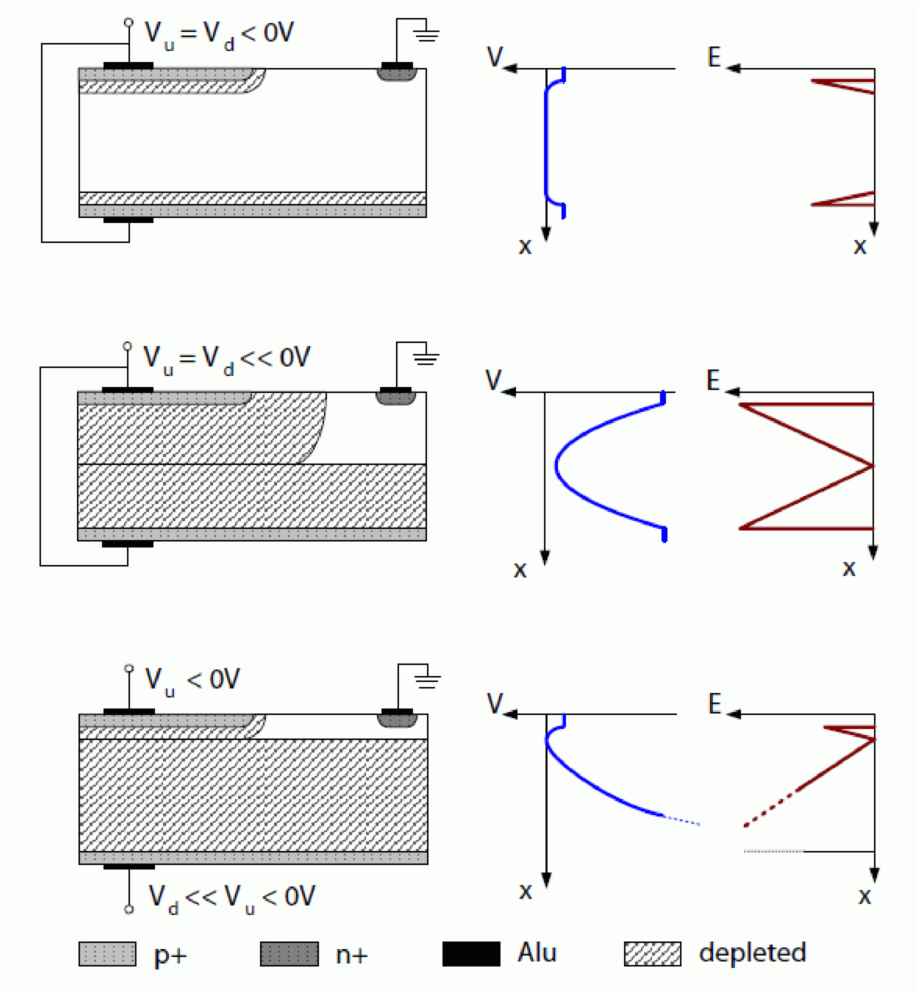


DEPFET DUT is steered by the EUDET DAQ software

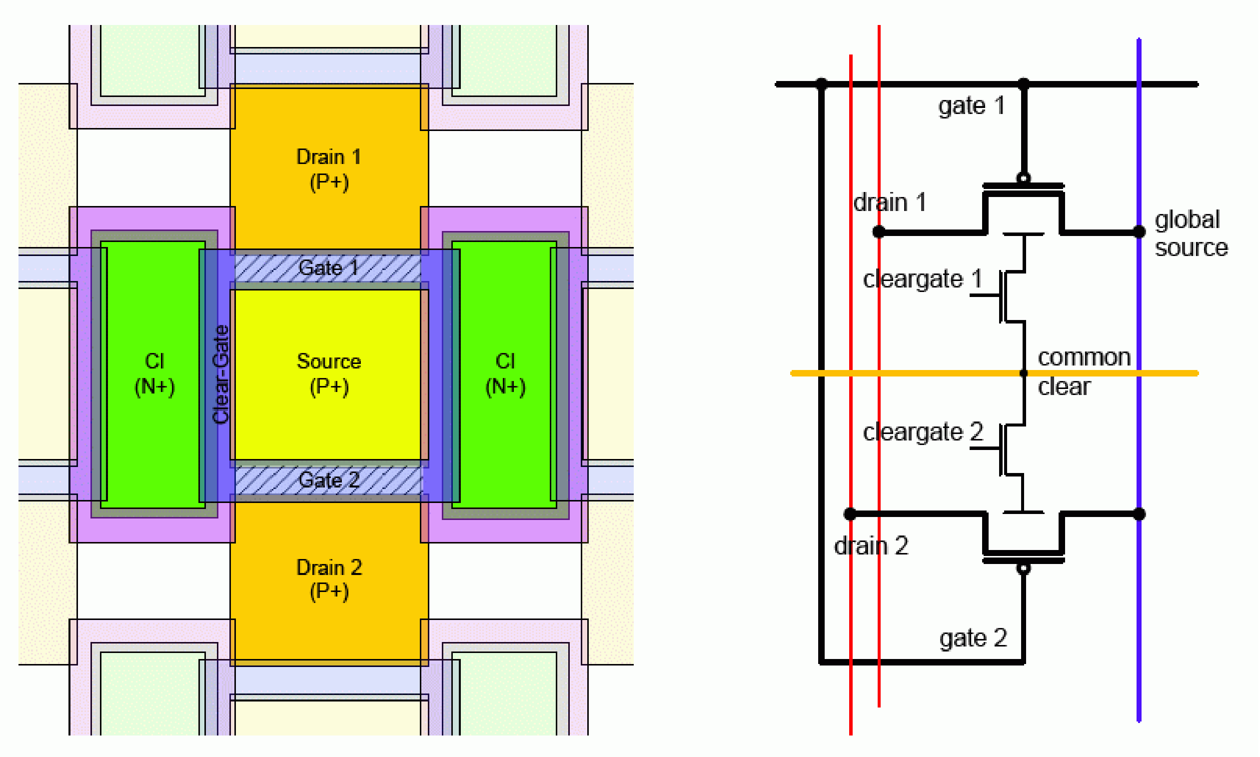


EUDET Run Control DEPFET Run Control

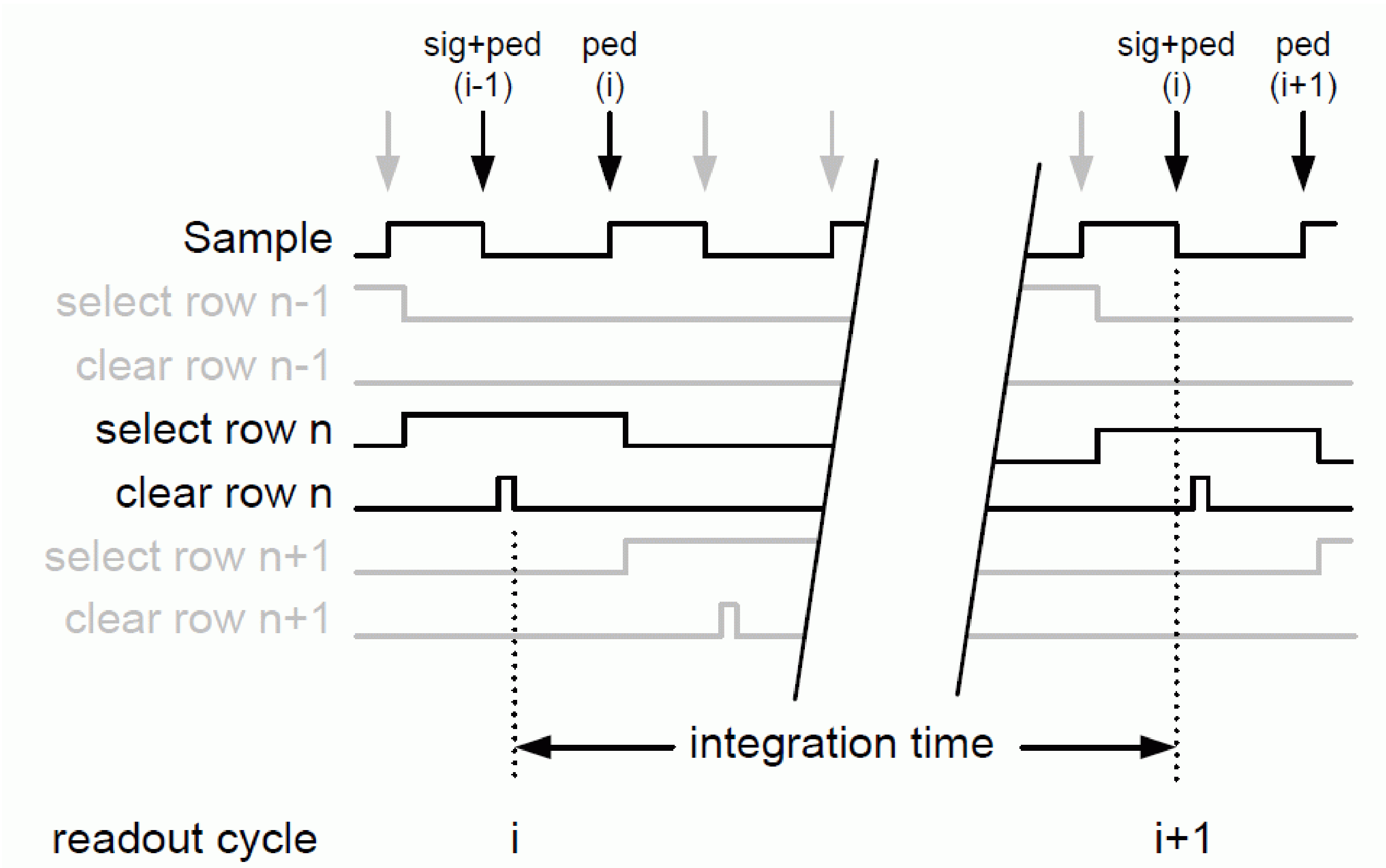
DEPFET sidewards depletion



DEPFET double pixel cell



DEPFET readout sequence



The in-pixel gain

- *The most probable signal is used to determine g_q :*

$$g_q(nA/e-) = \frac{\mu \times 7.7(nA/ADC)}{E_{MPV}(keV)/3.6(e^-/keV)}$$

- *Where :*
  - μ is the most probable value in ADU :
    - The 7.7 nA/ADC corresponds to the measured gain of the CURO/S3B system
  - E_{MPV} is the most probable energy deposition in 450 μm of silicon by 120 GeV pions:
    - EMPV = 131 keV (or equivalently 36.400 e–)

The in-pixel gain of different DEPFET prototypes

sensor type, matrix & pixel size			results	
name	row × column	(μm^2)	$g_q(pA/e^-)$	noise
telescope TB2008	128 × 64	32 × 24	320 ± 20	320 ± 20
DUT 2008	128 × 64	24 × 24	360	284
telescope TB2009	128 × 128	32 × 24	394 ± 14	290 ± 2
DUT CCCG	128 × 128	32 × 24	507	225
DUT short gate	128 × 128	20 × 20	655	174

Operation voltages of DEPFET

- *Power consumption of a DEPFET matrix*
- *Due to the row wise addressing the power consumption does not depend on the number of rows but only on the number of columns.*
- *The factor 2 takes into account the splitting of the matrix into two readout directions*

$$P = 2 * I_d * V_{ds} * n_{col} = 2 * 100\mu A * 5V * 64 = 64\ mW$$

- *The power necessary to ramp up and down the gate and clear lines is mainly consumed in the Switchers*

Operation voltages of a DEPFET matrix with respect to source (0V)

	Collection	Read	Clear
V^{*}_{Gate}	$3V$	$-2V$	$-2V$
V^{*}_{Clear}	$2V$	$2V$	$15V$
V^{**}_{Drain}	$-5V$		
$V_{ClearGate}$	$-2V$		
V_{Bulk}	$10V$		
V^{***}_{Back}	$-10V ... -50V$		

- $*$ control lines (transferred via Switcher)
- $**$ provided by readout input stage
- $***$ depending on final detector thickness and contact mode

Network DAQ, logic view