From 3D to 5D tracking: SMX ASIC-based Double-Sided Micro-Strip detectors for comprehensive **space, time, and energy measurements**

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Marcel Bajdel[1,2], Lady Maryann Collazo Sanchez[1,2], Ulrich Frankenfeld[2] Johann Heuser[2],
Hans Rudolf Schmidt[2,3], Joerg Lehnert[2], Shaifali Mehta[3], Dairon Rodriguez Garces[1,2],
Dario Alberto Ramirez Zaldivar[1,2], Christian Joachim Schmidt[2], Alberica Toia[1,2]

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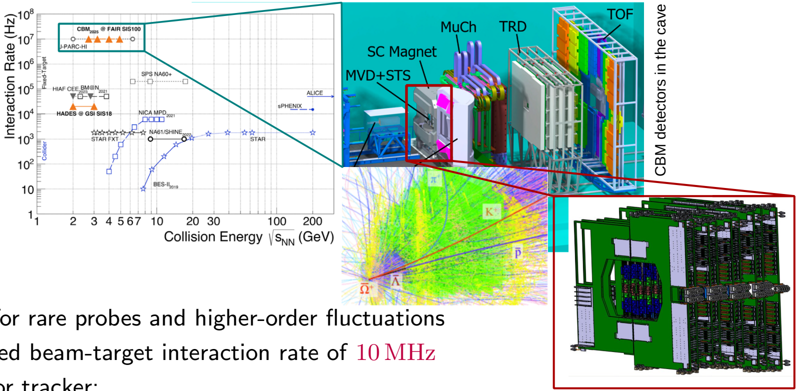
October 6, 2023

TWEPP 2023 Topical Workshop on Electronics for Particle Physics

Silicon Tracking System of the CBM experiment

core detector for rare probes of compressed nuclear matter in high-rate heavy-ion collisions



Silicon Tracking System

- CBM looks for rare probes and higher-order fluctuations
- Unprecedented beam-target interaction rate of $10\,\mathrm{MHz}$
- Challenges for tracker:
  - $\lesssim 700$ tracks in aperture /interaction, high granularity
  - low momenta $\rightarrow$ low material budget $(2-8\%\,X_0)$
  - $\Delta p = 1-2\%$ (evt. in B=1T)
  - spatial $(< 30\,\mu\mathrm{m})$ + timing $(< 5\,\mathrm{ns})$ + amplitude $(15\,\mathrm{fC}/5\,\mathrm{bit})$ in free-streaming mode

nXYTER: ASIC that measures time and amplitude

- nXYTER was a dedicated ASIC for (ToF and Imaging) neutron detectors
  - one of applications: double-sided Silicon micro-strip detector
    (coupled to a Gadolinium neutron-converter layer)

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Nuclear Instruments and Methods in Physics Research A 568 (2006) 301–308
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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N-XYTER, a CMOS read-out ASIC for high resolution time and amplitude measurements on high rate multi-channel counting mode neutron detectors

A.S. Brogna[d], S. Buzzetti[a,*], W. Dabrowski[b], T. Fiutowski[b], B. Gebauer[c], M. Klein[d], C.J. Schmidt[d], H.K. Soltveit[d], R. Szczygiel[b,e], U. Trunk[d]

nXYTER: ASIC that measures time and amplitude

- nXYTER was a dedicated ASIC for (ToF and Imaging) neutron detectors
  - one of applications: double-sided Silicon micro-strip detector
    (coupled to a Gadolinium neutron-converter layer)
  - two paths after CSA: slow (amplitude) and fast (time)

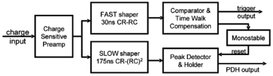


Fig. 1. Block diagram of a single channel of the realized ASIC.

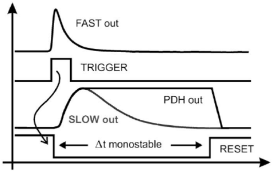
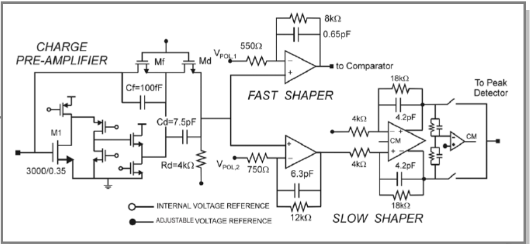


Fig. 2. Diagram illustrating the main signals inside the ASIC.



…YTER, a CMOS read-out ASIC for high resolution time and amplitude measurements on high rate multi-channel counting mode neutron detectors

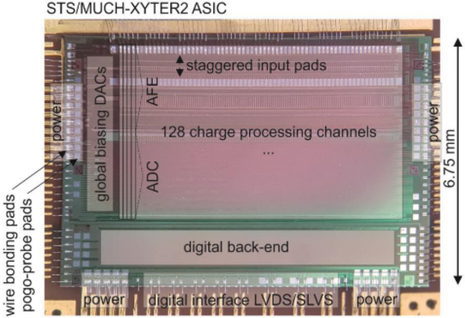
…rogna[d], S. Buzzetti[a,*], W. Dabrowski[b], T. Fiutowski[b], B. Gebauer[c], M. Klein[d], C.J. Schmidt[d], H.K. Soltveit[d], R. Szczygiel[b,e], U. Trunk[d]

- Analogue memory, external ADC required

Latest Generation: STS-MUCH-XYTER v 2.2

Features of the ASIC:

- Low-power, self triggering AISC
- 128 channels + 2 test channels
- Time resolution $\lesssim 5\,\mathrm{ns}$
- Provides digitized hits with:
  - 5 bit energy resolution
  - 14 bit time stamp
- Linearity range up to $15\,\mathrm{fC}$ $(100\,\mathrm{fC})$
- **Flash ADC + digital buffer** integrated in ASIC

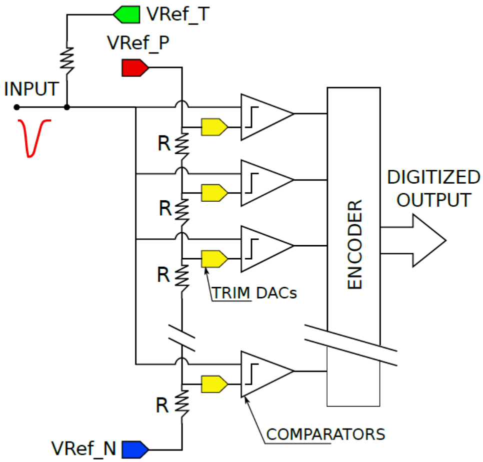


K. Kasinski *et al* Nucl.Instrum.Meth.A 908 (2018)

Current status:

- ASIC production yield 98.5%–99.0%, chip cable yield 96%
- **production:** ~ 4000 available for series module production
- 360 dies per wafer, 100 wafers produced

Amplitude measurement with SMX flash ADC



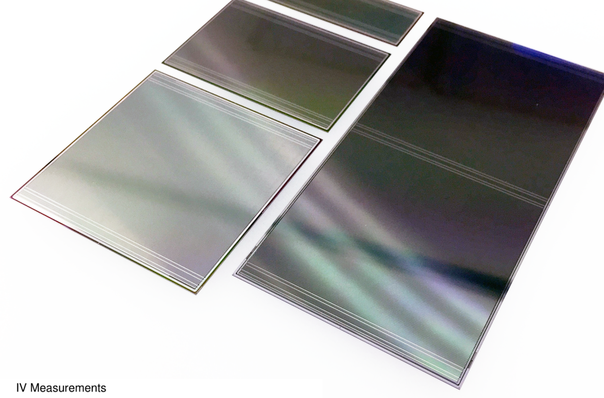
5-bit flash ADC (Analog-to-Digital Converter)

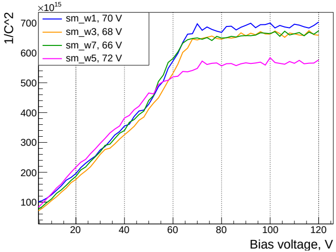
- 1 ADC/channel
- 5-bit resolution
- $2^N - 1$ comparators
- Up to 15 fC (100 fc) in STS (MUCH) mode
- Trimming circuit with 8-bit resolution
- Diagnostic counter for each discriminator

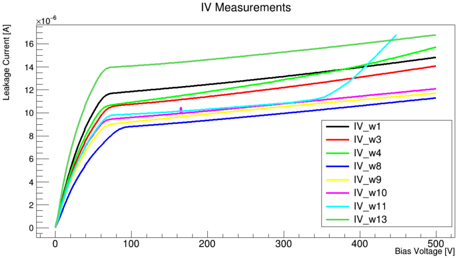
Detector module components and construction

DSDM silicon micro-strip sensors

- Double sided n-type silicon sensors (XY positioning): 1024 strips each side, p-side tilted by 7.5° to the edge
- **Thickness** $320\,\mu m \pm 15\,\mu m$
- **Pitch size** $58\,\mu m$ for both sides
- 62 mm × 22 mm, 42 mm, 62 mm or 124 mm
- Strip coupling capacitance (n) $14.1 \pm 0.1\,\mathrm{pF/cm}$ interstrip capacitance $0.37 \pm 0.01\,\mathrm{pF/cm}$

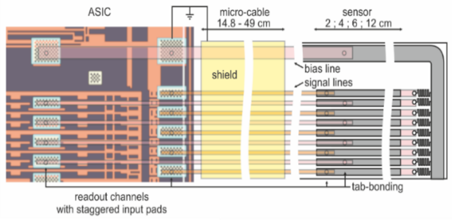




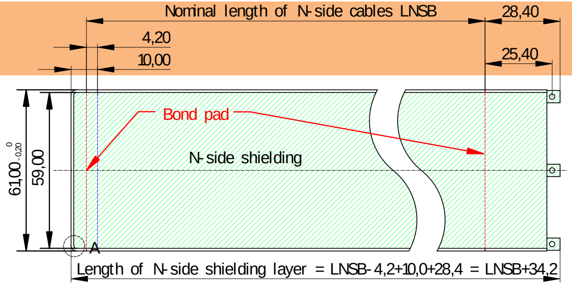


Ultra-thin r/o micro cables

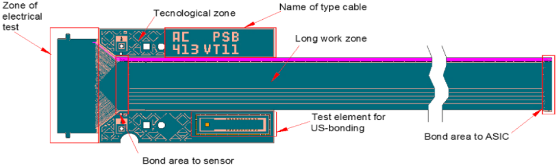
- FEE connected via micro-cable lines (64 lines/cable)



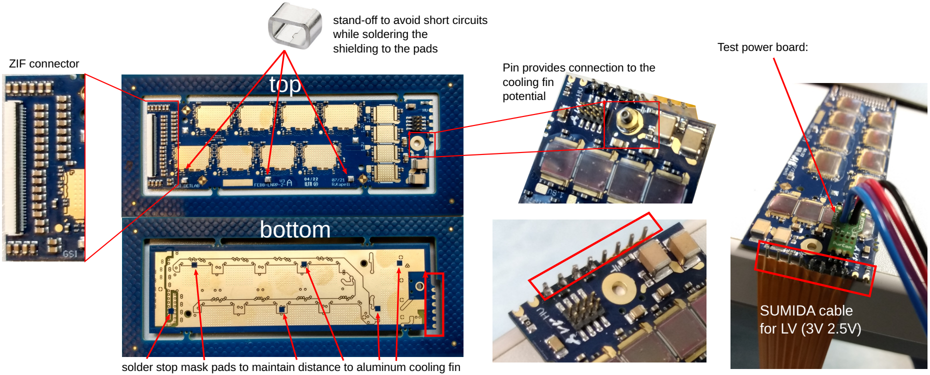
- 2×1024 ch./sensor: stack of 32 micro cables per module, 8 sub types
- Length from 160 mm to 495 mm



↗ Read-out lines are protected w/ shielding layers



FEB mechanical and electrical features

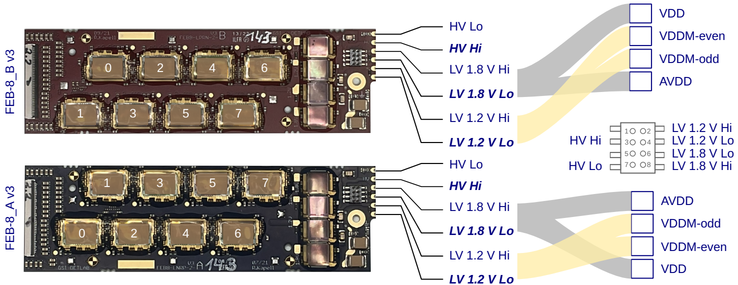


- Data lines + clock: 40 or 100 lines (FEB8_2/FEB8_5)
  - HV decoupling w/ capacitors
  - ZIF connector for data cable
- Ground interfaces through PCB to cooling fin
  - service connector for testing
  - permanent soldering at the edge to the flat LV cable + coax. HV cable

Powering and grounding of the STS FEE

LV/HV channels and voltage stabilization

Schematics of FEB-8 v3+:

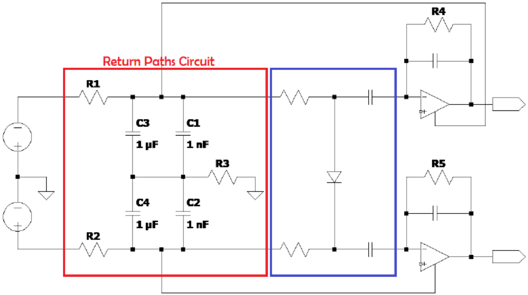


- AC coupling capacitors for FEB operation at bias potential
- Two low voltage lines with 1.2 V and 1.8 V are powering ASICs
- Custom low-noise LDOs are used for stabilization of the voltage
- Return path circuit for HV and GND implemented on a FEB since v3

Powering and grounding of the STS FEE

return path circuit

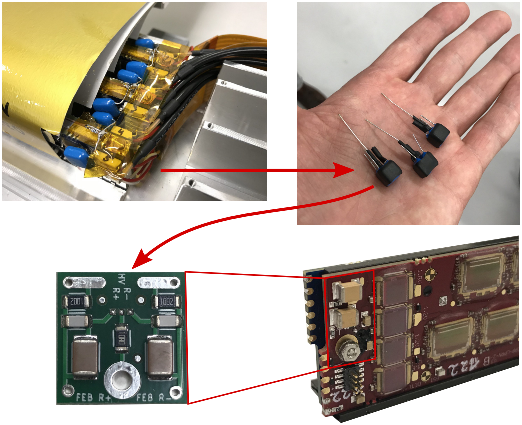
- Dedicated circuit with discrete components:
  - filters HV potential
  - stabilization of the floating HV potential
    - between module sides (crucial for noise performance)
    - to the GND point (important for synchronization)



- Optimisation of the values of the components followed

Return path circuit: from concept to implementation

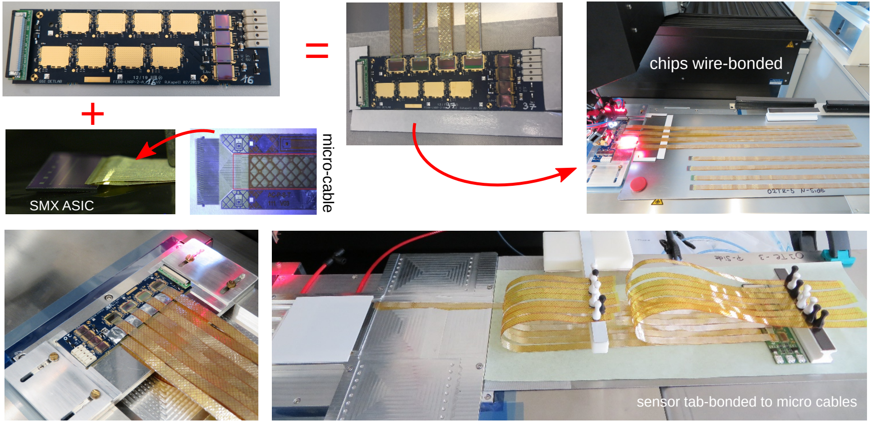
- Few iterations of design and prototyping:



- Return path circuit is a part of the current FEB8 design

Composition and assembly of the detector module

- STS detector modules are produced in the assembly centres in GSI and KIT
  - highly integrated objects: extensive testing at each step



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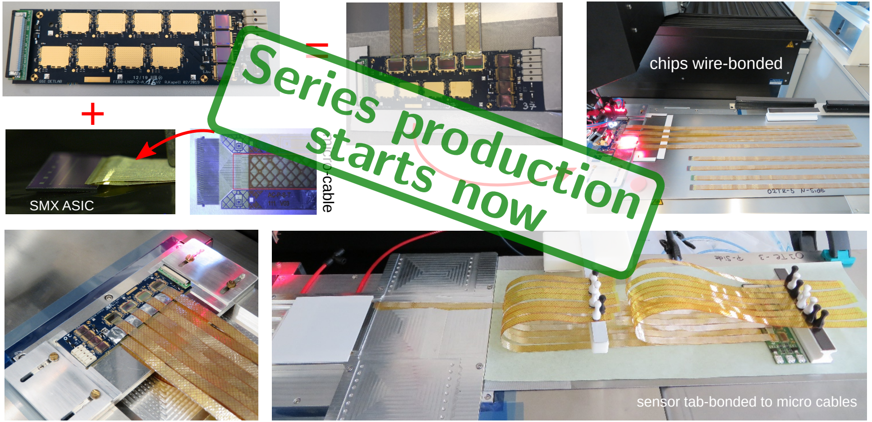
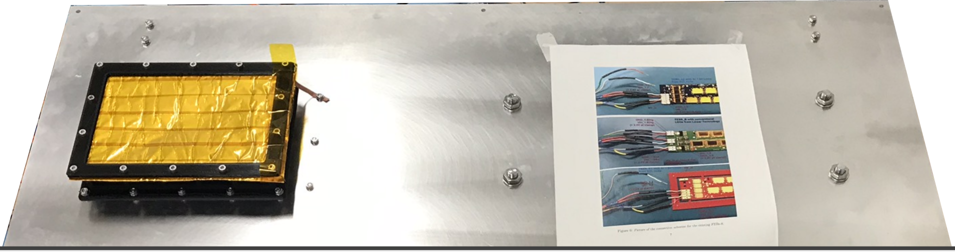
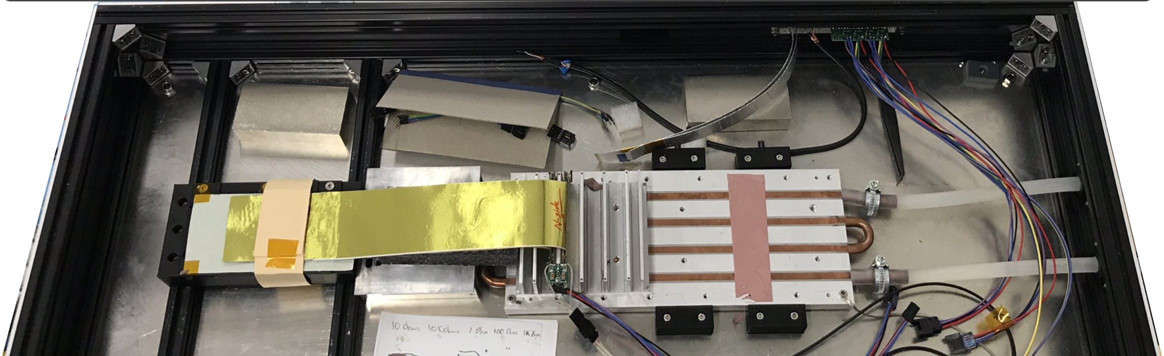


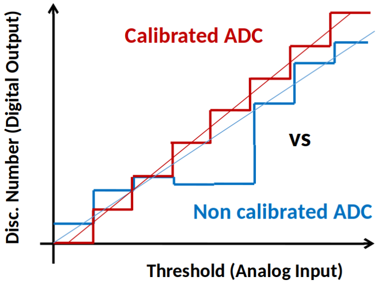
- Successful pre-series production for the E16 J-PARC experiment



Module calibration and tests



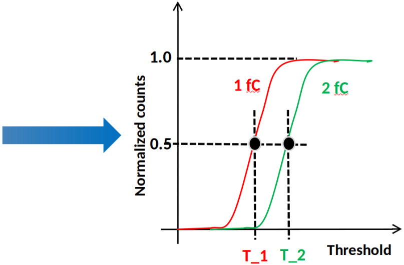
Calibration procedures for the SMX ASIC



- To develop a calibration procedure for the ADC and FAST discriminator that allows to achieve:
  - linear behavior
  - homogeneous response among all channels
  - absolute charge calibration
- Uses the internal test charge generation
- Should be fast, accurate, reproducible and scalable to series production

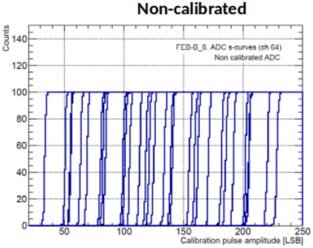
How to calibrate the flash ADC?

- Performing a threshold scan for every discriminator (31 disc/channel).
- Finding the middle point (50%) in the discriminator response for a fix injected charge

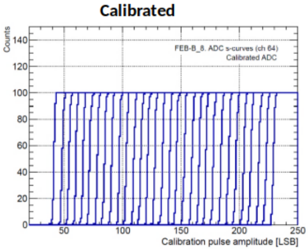


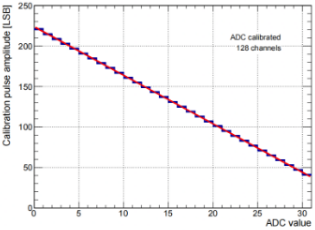
Example of ASIC calibration

unique for each ASIC and calibration range



VS





Findings

- Calibration ensures linearity and reduces the spread among the channels up to 10 times
- Cross-checked using external pulse generator and ^{241}Am source
- Procedure established for module production/ setup operation
- Stable over time (Long run stability tests)

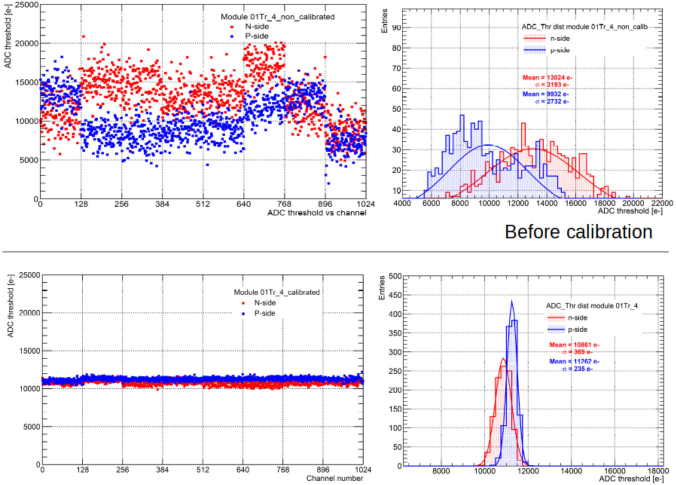
Example of ASIC calibration

threshold equalisation

- Calibration of the measuring circuits on each ASIC is one of the first steps during the evaluation of the module performance after assembly

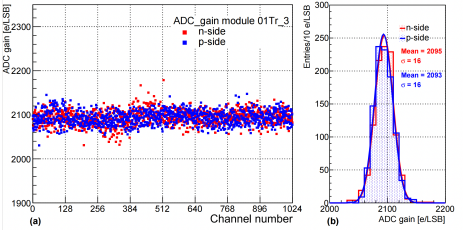
Findings

- Verification of the calibration algorithms and circuits as in previous versions
- ADC linearity achieved in the measuring range
- Spread among channels reduced 10 times after calibration
- Homogeneous performance for both polarities



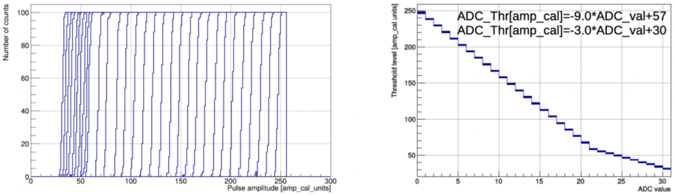
SMX slow path gain after the calibration

- After the charge calibration the output in ADC-units is proportional to the injected charge
- Linear calibration
- Constant gain across dynamic range:



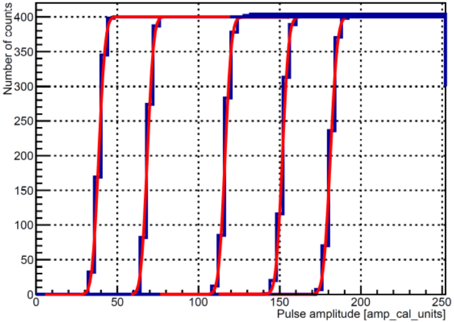
- Non-linear calibration possible
  - fine resolution at lower amplitudes?

VRef_N = 27 (@90 pulses, range: 40, iterations: 25)



Noise measurement in the SMX ASIC

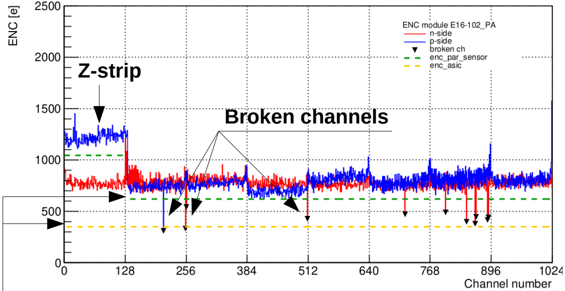
- Equivalent Noise Charge (ENC) derived from an S-curves scan in every channel, where the discriminator response is evaluated in a pulse amplitude scan



- The response function of each discriminators in a channel are fitted with erfc.
  - μ represents the effective discriminator threshold
  - σ represents the ENC value in units of the internal pulse generator

Overall noise performance

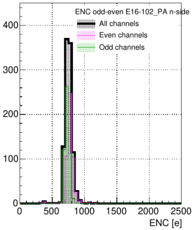
Low noise ($\simeq$ dark rate) is essential for the free-streaming detector operation

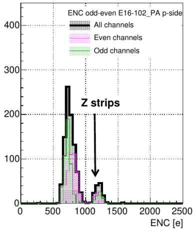


$$ENC = \left[\underbrace{L_{\text{sensor}} \cdot 1.02\,\frac{\text{pF}}{\text{cm}}}_{\text{sensor}} + \underbrace{L_{\text{cable}} \cdot 0.38\,\frac{\text{pF}}{\text{cm}}}_{\text{microcable}}\right] \cdot 25\,\frac{\text{e}}{\text{pF}} + \underbrace{350\,e}_{\text{ASIC}}$$

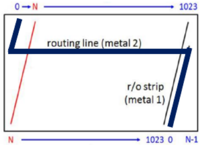
Z-strip: 17 pF extra from the double metal routing

***I.Panasenko**, PhD thesis*





Z channels interconnected via a double metal layer



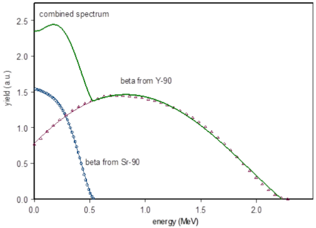
Estimate the extra capacitance Z-strip: $\Delta(ENC_{Z\text{-strip}} - ENC_{ave})$

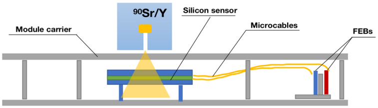
- Lower noise of the broken channels used for QA purposes

Signal in the detector: test with ^{90}Sc

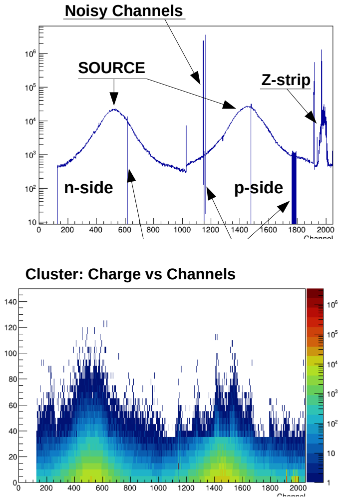
Source ^{90}Sr/Y

- Beta-emitter
- electron with spectrum larger than 1 MeV
- placed at the center of the sensor





Experimental setup

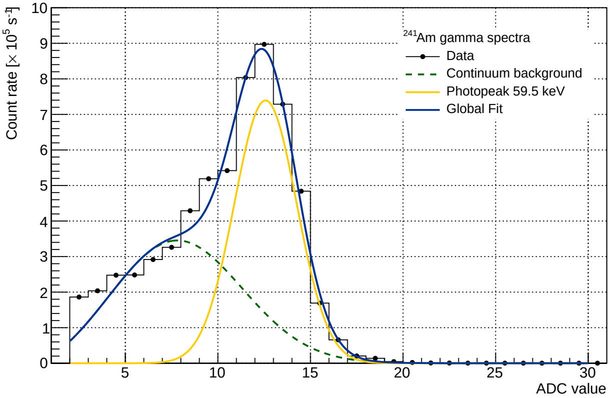


- ▶ Data taken with CBM GBTx-based DAQ chain

Vladimir Sidorenko Oct 2 TWEPP2023

Signal in the detector: test with ^{241}Am

- Ultimate test of the detector amplitude response
- Cross-check of the detector calibration

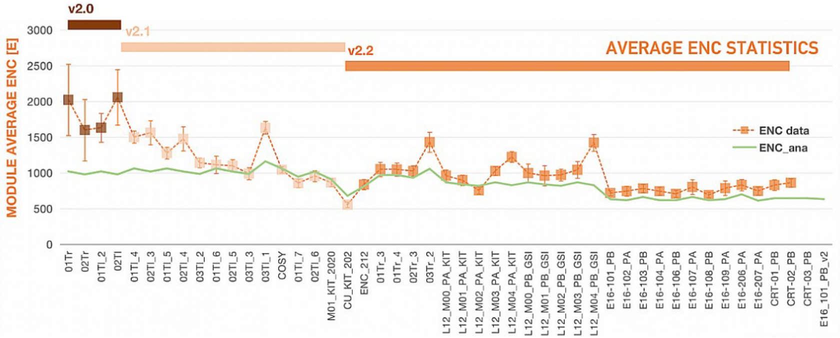


- Studies and experience are summarised in the paper submitted to NIM:

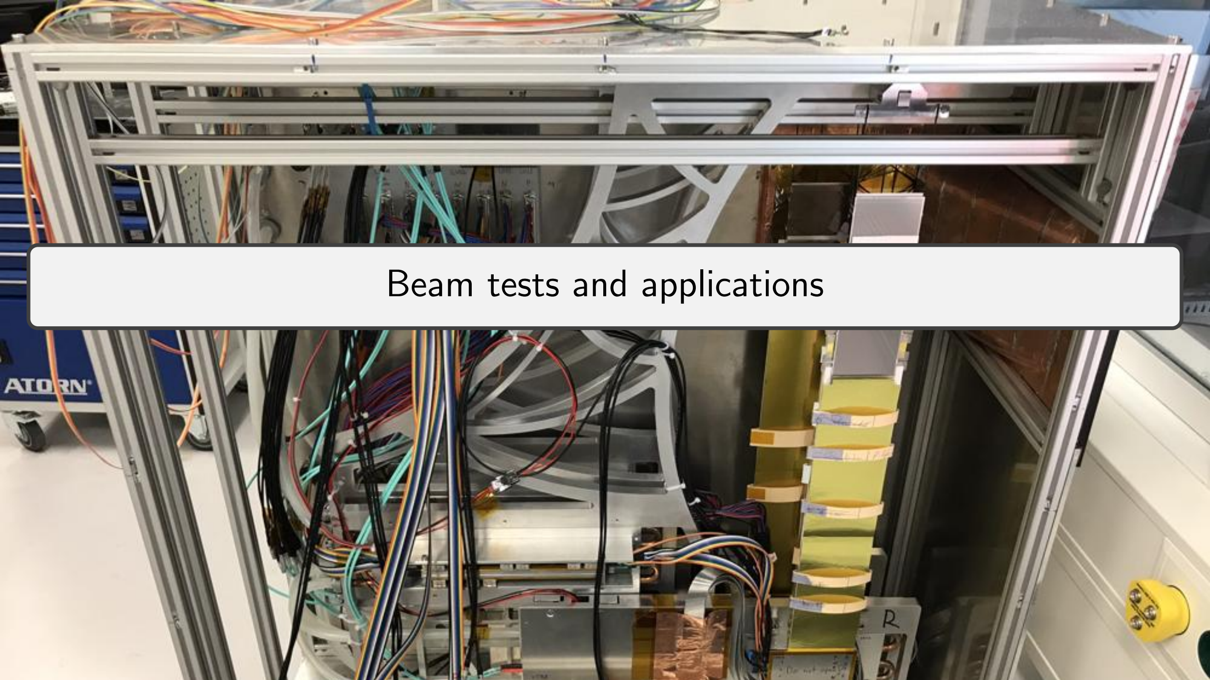
Functional characterization of modules for the Silicon Tracking System of the CBM experiment

A. Rodríguez Rodríguez[a,*], O. Maragoto Rodríguez[a], J. Lehnert[a], A. Toia[a,b], M. Teklishyn[a,c], A. Lymanets[a], D. Rodríguez Garcés[a,b], J. M. Heuser[a], C. J. Schmidt[a]

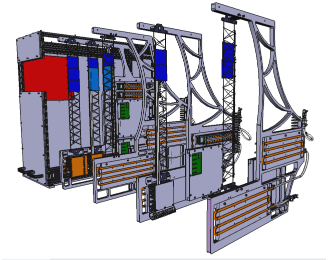
[a] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, Darmstadt, 64291, Germany*
[b] *Goethe Universität, Max-von-Laue-Str. 1, Frankfurt am Main, 60438, Germany*
[c] *Institute for Nuclear Research, Prospekt Nauky 47, Kyiv, 03680, Ukraine*

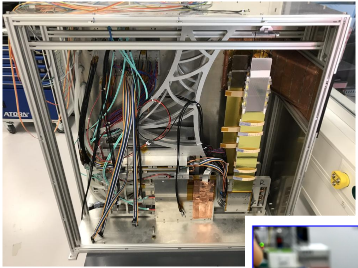


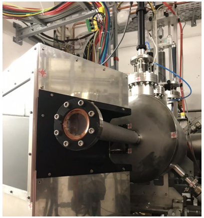
Beam tests and applications



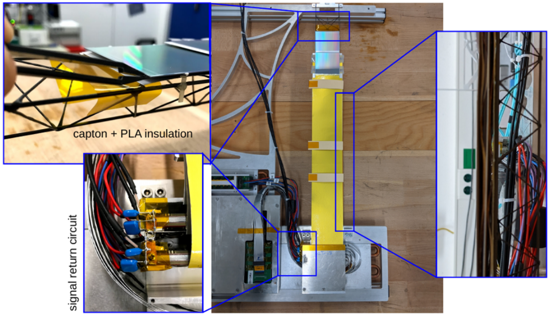
mSTS: functional full-scale detector prototype





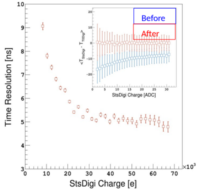


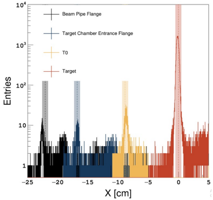
- Two tracking stations (layers) $12 \times 12\,\mathrm{cm}^2$ and $18 \times 18\,\mathrm{cm}^2$ arranged by 4 units
- Ultimate test of the detector performance **in the fully integrated system**
- Commissioning of the **assembling and testing procedures** to be used in series production
- Hit/track reconstruction performance with the **heavy ions in mCBM@SIS18 (GSI, Darmstadt)**



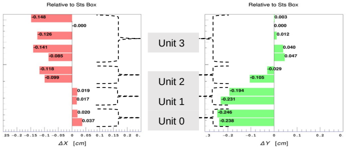
mSTS: recent beam-test highlights

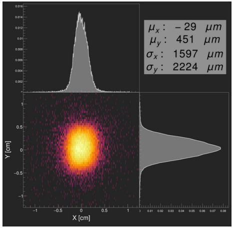
Dario A. Ramirez Zaldivar at VERTEX 2023



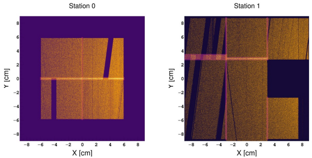


Sensor alignment translations are consistent with the mechanical assembly!

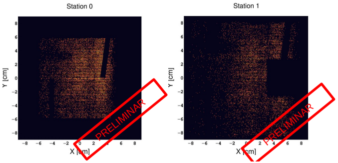




MC HRE >99.98%



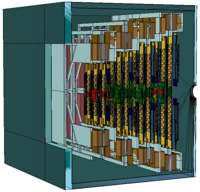
mCBM HRE >96.88%
Excluding inactive areas

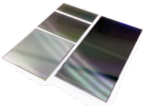


- Testing the free-streaming data acquisition system; data transport to a high-performance computer farm
- Online track and event reconstruction as well as event selection algorithms

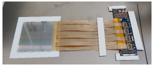
STS goes to Japan: synergy with E16 experiment

CBM-STS





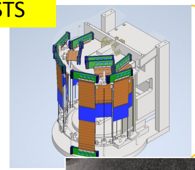
Silicon Sensors (Hamamatsu)

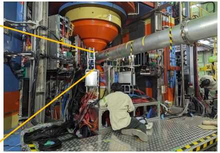


Sensor, cables, and Front-end electronics

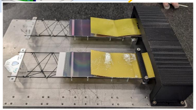
Sent to Japan for performance check

E16-STS

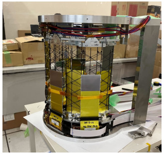




Spectrometer



Sensor, ladder, cable



E16-STS

CBM-STS is in the construction phase

Construction and operation methods will be improved by feedbacks from Japan

- Knowledge of constructions and operations and performance of total system are useful
- Experienced PD and student from KEK will join the CBM-STS construction

Feedback

E16-STS is installed and will be tested in the next year

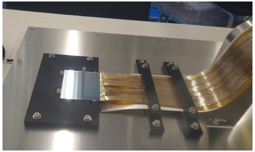
Performance will be evaluated in high-rate counting situation

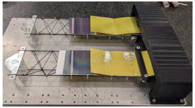
- 10MHz interaction rate

K. Ozawa @ 42th CBM Collaboration Meeting, September 28 2023

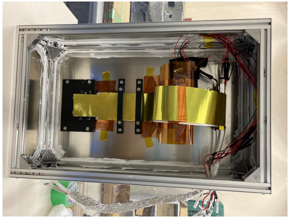
E16 STS installation, commissioning and tests

- 10 modules are used in the E16 experiment at J-PARC

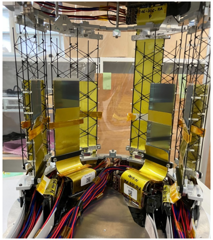


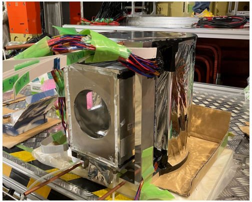


Sensor, ladder, cable

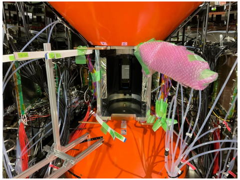


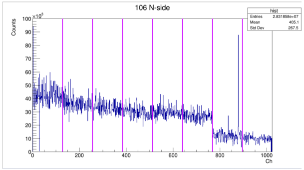
Test Chamber





E16 STS





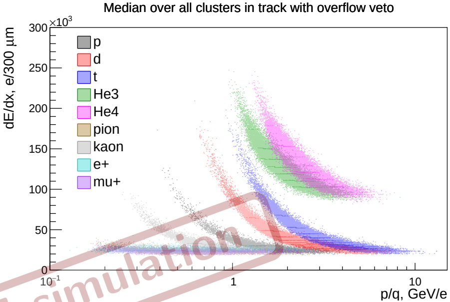
Obtained Profile

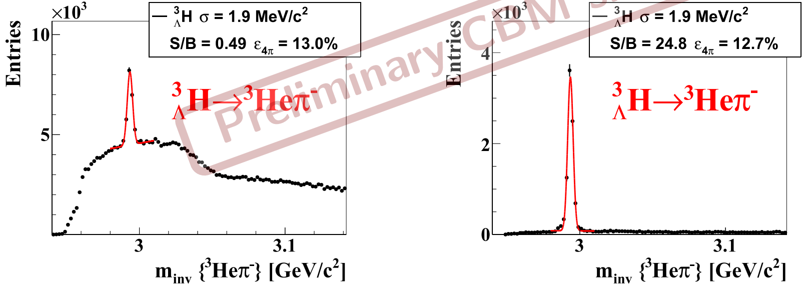
K. Ozawa @ 42th CBM Collaboration Meeting, September 28 2023

Simulation of PID with STS

$\Delta E/\Delta x$ information for hypernuclei

- The strongest discrimination expected for He/H
- Natural implementation in hypernucleus analysis
  - TOF PID only, significant background (left)
  - TOF + STS PID combined, almost zero background (right)
    - single criteria of $\Delta E_{\text{median}} > 75\,\text{ke}$ for ^3He, $\forall p$





5M UrQMD Au Au $10A\,\text{GeV}$ events

Analysis by Iouri Vassiliev and Maksym Zyzak for the CBM Collaboration

Summary, present and future use

Current status:

- Series production started for CBM STS
- Various pre-series batches under study
  - cosmic ray telescope

System characteristics

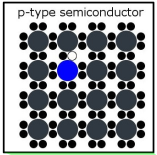
- $320\,\mu\text{m}$ thick sensor ($\simeq 3‰ X_0$)
- $\Delta X \simeq 58/\sqrt{12}\,\mu\text{m}$ or better
- FEE up to 0.5 m away
- amplitude up to 15 fC (100 fC) in 31 bin
- time $\Delta t \simeq 5\,\text{ns}$
- self-triggering for each channel

Applications (present and future):

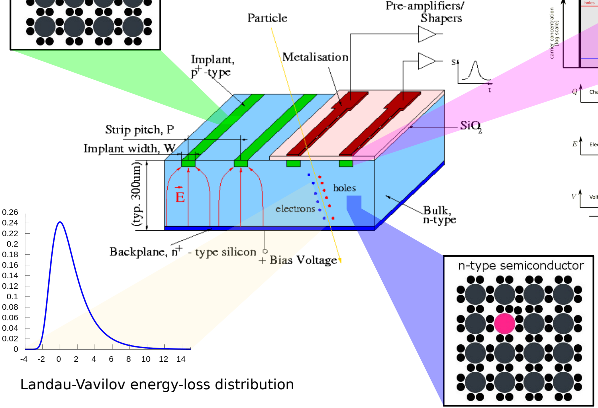
- Core tracker of the fixed-target future heavy ion CBM experiment at FAIR
- First tracking layer of E16 at JPARC
- Reaction-product/beam monitor for radiation treatment
- **We are open for new ideas!**

Back-up slides

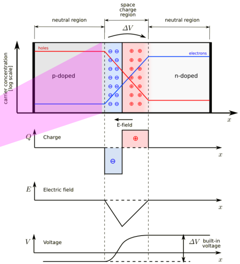
Silicon micro-strip detectors



Well-established, reliable and cheap (~1$/channel) technology

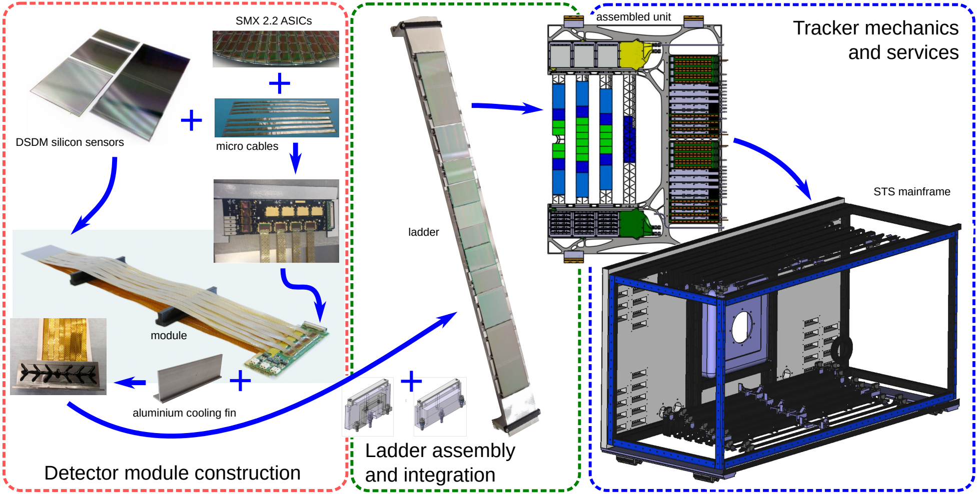


Landau-Vavilov energy-loss distribution

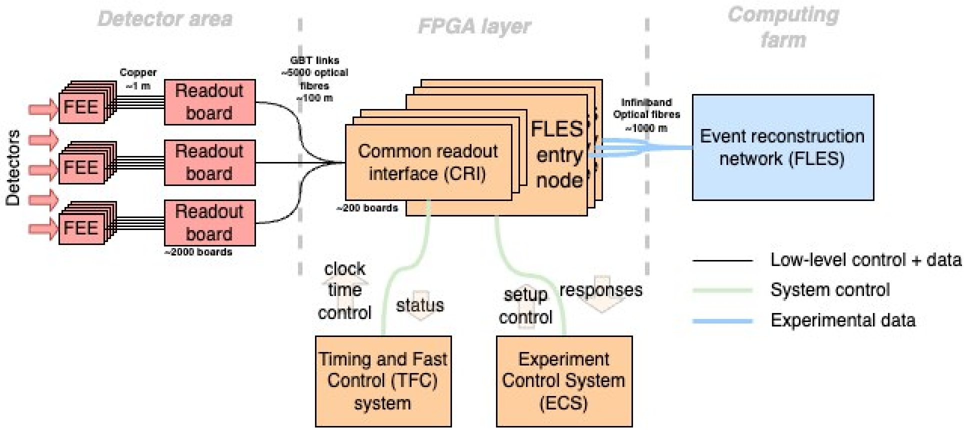


p-n junction effect
+ bias voltage

STS assembly sequence and structure

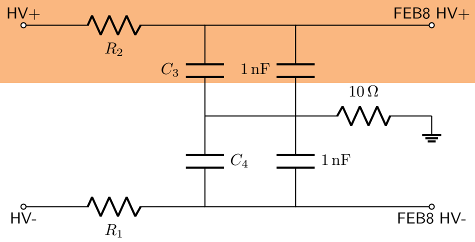


STS DAQ chain



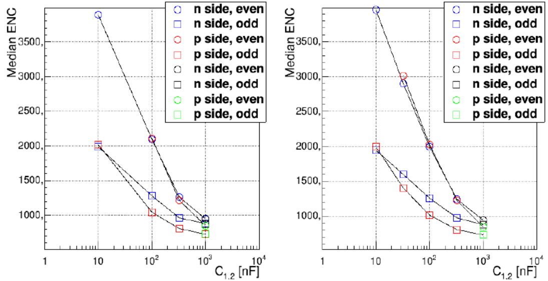
Return path circuit

component value optimisation



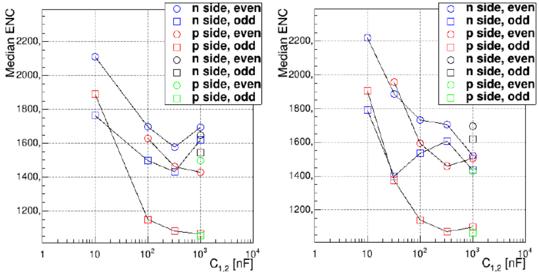
Slow channel, $C_{3,\,4}$ value scan

$R_{1,\,2} = 1\,k\Omega$ (left), $R_{1,\,2} = 10\,k\Omega$ (right):



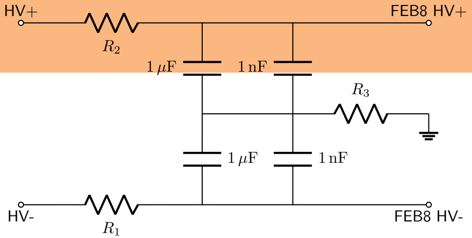
Fast channel, $C_{3,\,4}$ value scan

$R_{1,\,2} = 1\,k\Omega$ (left), $R_{1,\,2} = 10\,k\Omega$ (right):



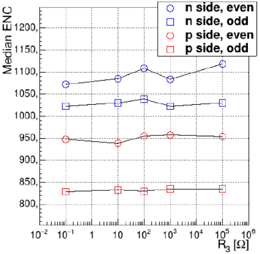
Return path circuit

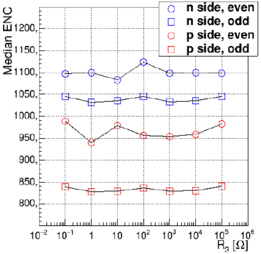
component value optimisation



Slow channel, R_3 value scan

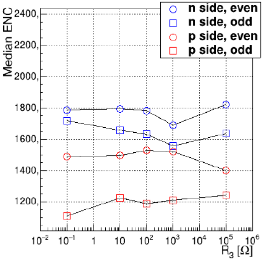
$R_{1,2} = 1\,k\Omega$ (left), $R_{1,2} = 10\,k\Omega$ (right):

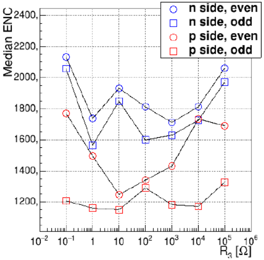




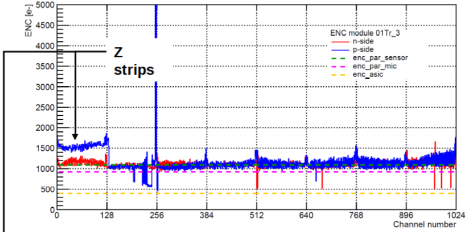
Fast channel, R_3 value scan

$R_{1,2} = 1\,k\Omega$ (left), $R_{1,2} = 10\,k\Omega$ (right):



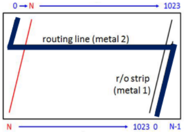


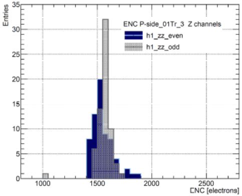
Channel-to-channel noise of the module



ENC distribution across 1024 channels in a module

Z channels interconnected via a double metal layer

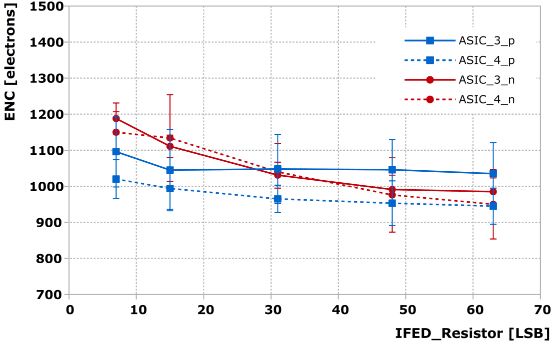


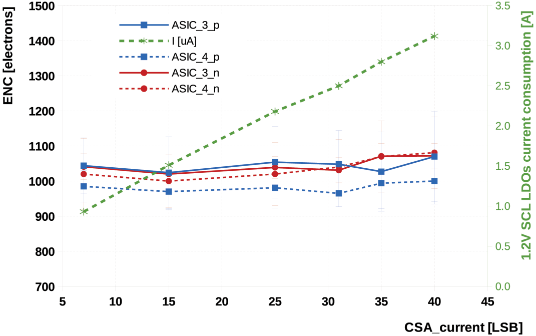


ENC distribution in Z channels

- Module ENC derived from S-curves scan, where the discriminator response is evaluated in a pulse amplitude scan
- "Higher ENC level in first p-side channels caused by interconnections via a double metal (Z channels)

Noise dependence on the SMX settings





- ENC levels stable for a large range of settings