Pixel detector development for the PANDA MVD

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on behalf of the PANDA MVD group

532. WE-Heraeus-Seminar on
Development of High_Resolution Pixel Detectors and their Use in Science and Society
Bad Honef, May 23-25, 2013

Outline

- Introduction to FAIR and PANDA
- The Micro Vertex Detector
- The pixel detector development
- Prototyping phase and first results
- Conclusions

Introduction

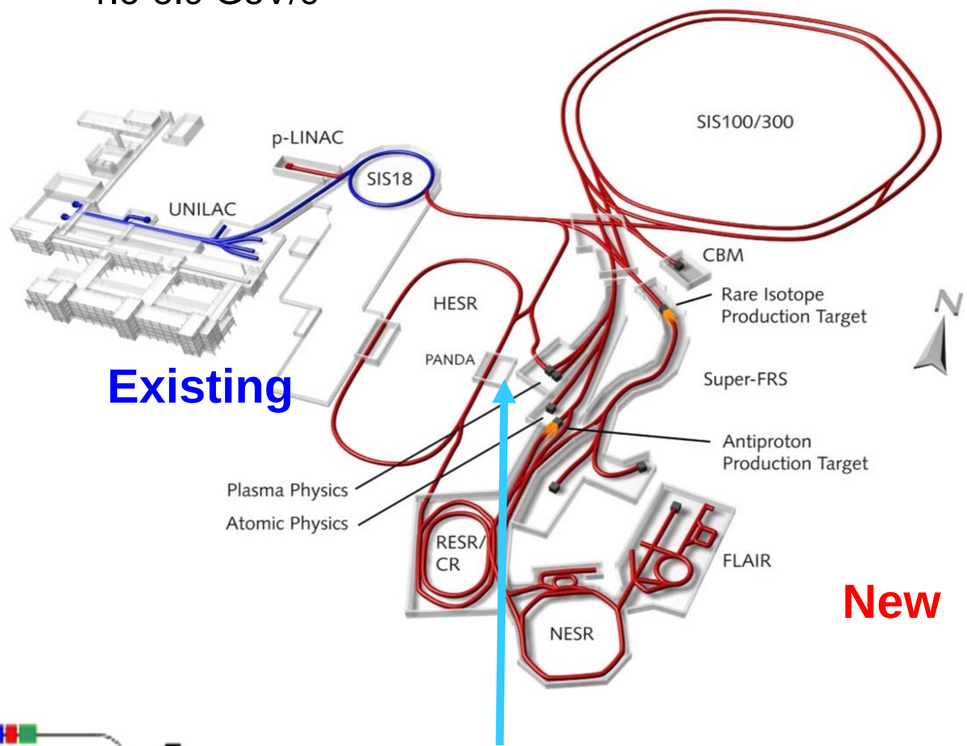
PANDA @ FAIR

Facility for Antiproton and Ion Research

- New facility at GSI near Darmstadt
- Proton, antiproton and ion beams will be available

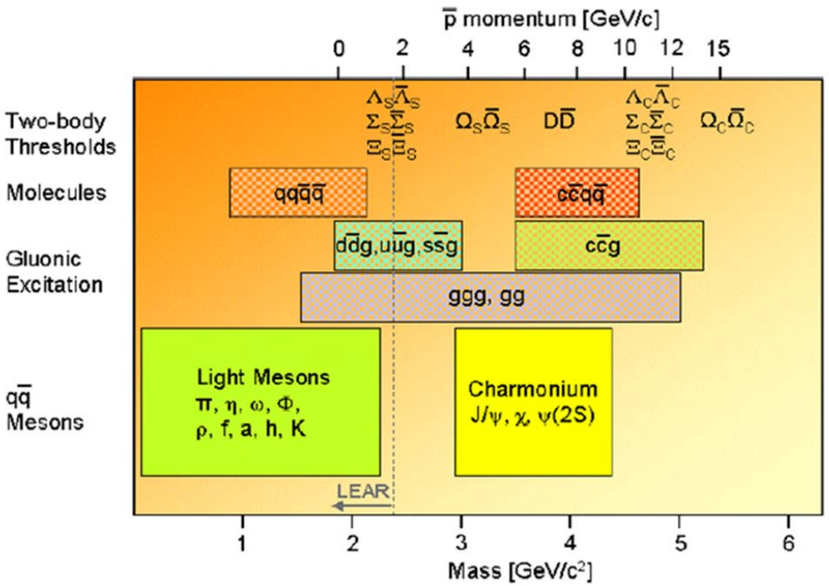
Antiproton beam at HESR – High Energy Storage Ring

- High luminosity ~ $2 \cdot 10^{32}$ cm^{-2} s^{-1} , $\delta p/p \sim 10^{-4}$
  1.5-15 GeV/c
- High resolution ~ $2 \cdot 10^{31}$ cm^{-2} s^{-1} , $\delta p/p \sim 4 \cdot 10^{-5}$
  1.5-8.9 GeV/c



antiProton Annihilation at Darmstadt

Physics @ PANDA

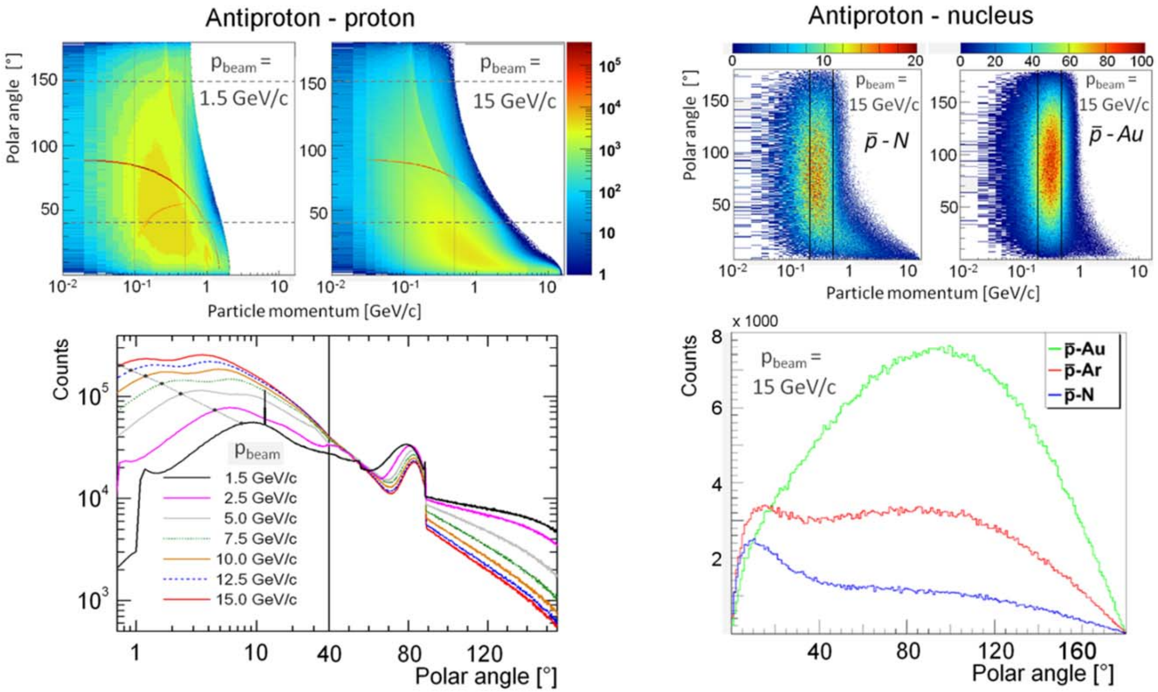


- Charmonium spectroscopy
- Search for gluonic excitations
- Study of hadrons in nuclear matter
- Hypernuclear physics
- Electromagnetic processes

Multipurpose apparatus with triggerless Data Acquisition @ high interaction rate ($2\cdot10^7$ pbar-p interactions /s)

Apparatus requirements

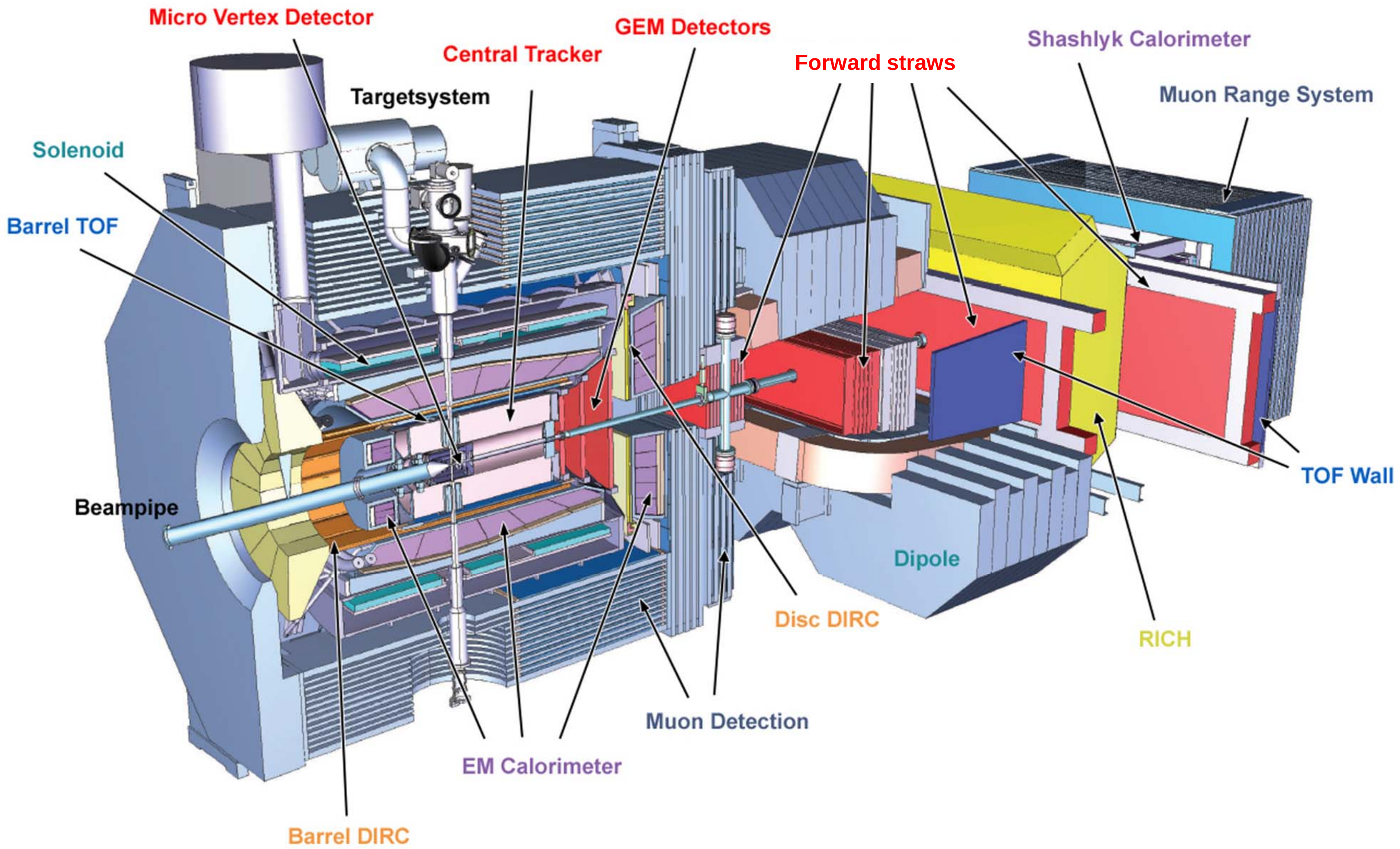
- Momentum resolution < 2 %
- Vertex info for D, K^0_s, Λ
- Good PID (e, μ, π, k, p)
- γ-detection 1 MeV – 10 GeV



Forward peak in pbar-p annihiliations and high polar angles in pbar-nucleus interactions

~ 4 π coverage

PANDA apparatus



Target spectrometer. 2T superconducting solenoid - Forward spectrometer. 2Tm resistive dipole

PANDA is a fixed target experiment

MVD layout

Micro Vertex Detector

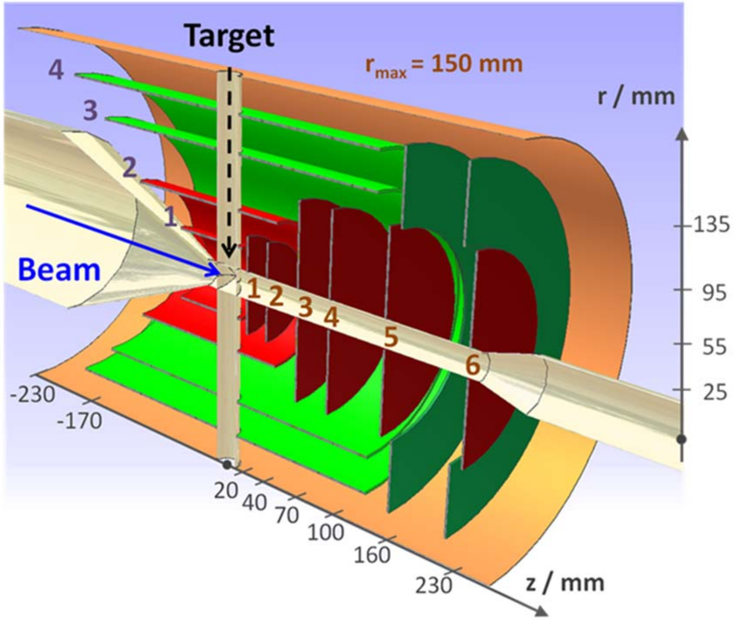
Tasks

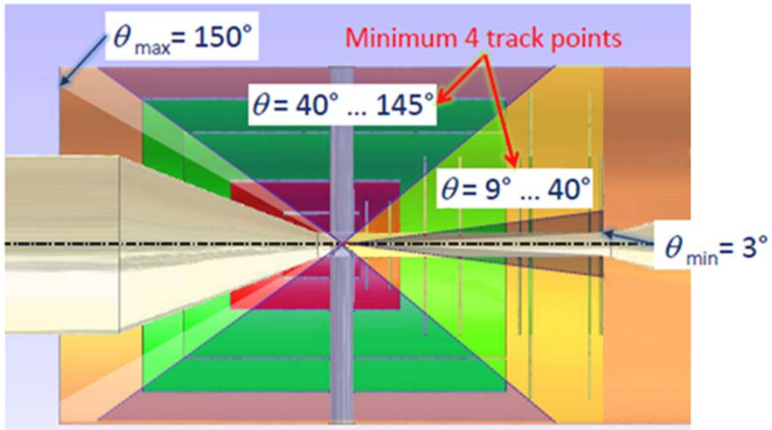
- It must combine good space resolution with accurate time-tagging
- Main functions:
  - ✓ Primary vertex reconstruction
  - ✓ Identification of the secondary vertices ($c\tau$ of some hundreds of μm)
  - ✓ Improvement in momentum resolution
  - ✓ Support PID of low momentum particles by energy loss measurement

Specifications

- Good spatial resolution (some tents in $\rho\phi$, better than 100 μm along z)
- Good time resolution: < 5 ns rms
- Continuous readout at 2 x 10^7 interactions /s (clock @155.52 MHz)
- Limited material budget
- Provide at least four hits per track
- Radiation fluence of 10^{14} n [1MeVeq] /cm^2
- Room temperature operation
- Routing and Services only in the backward region

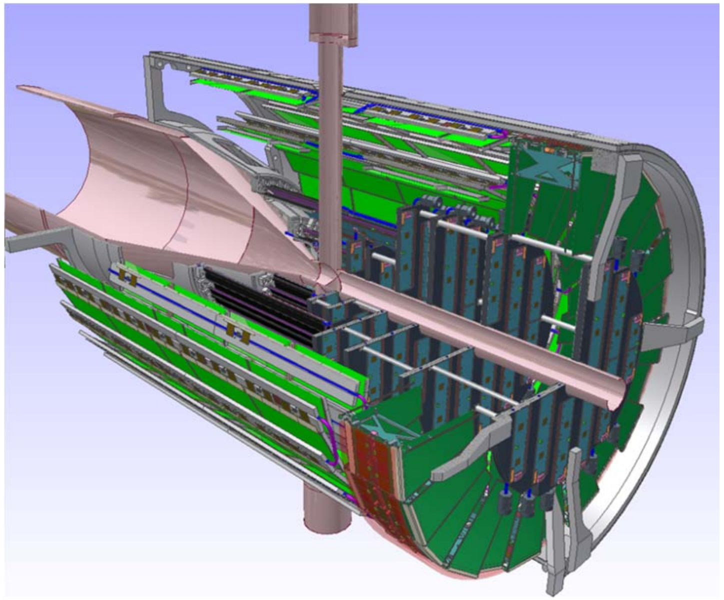
MVD layout

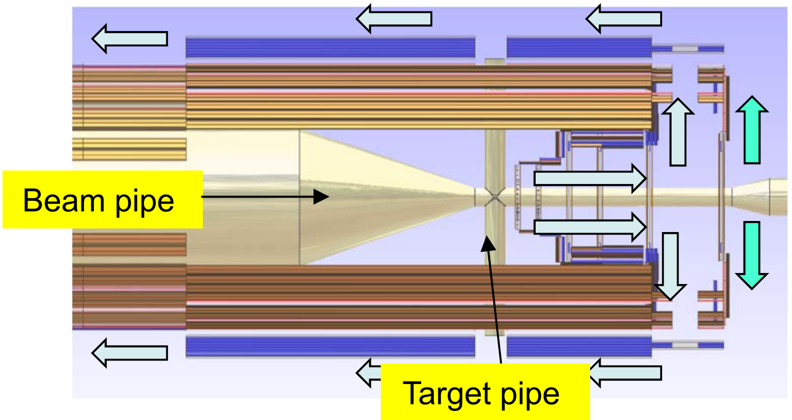


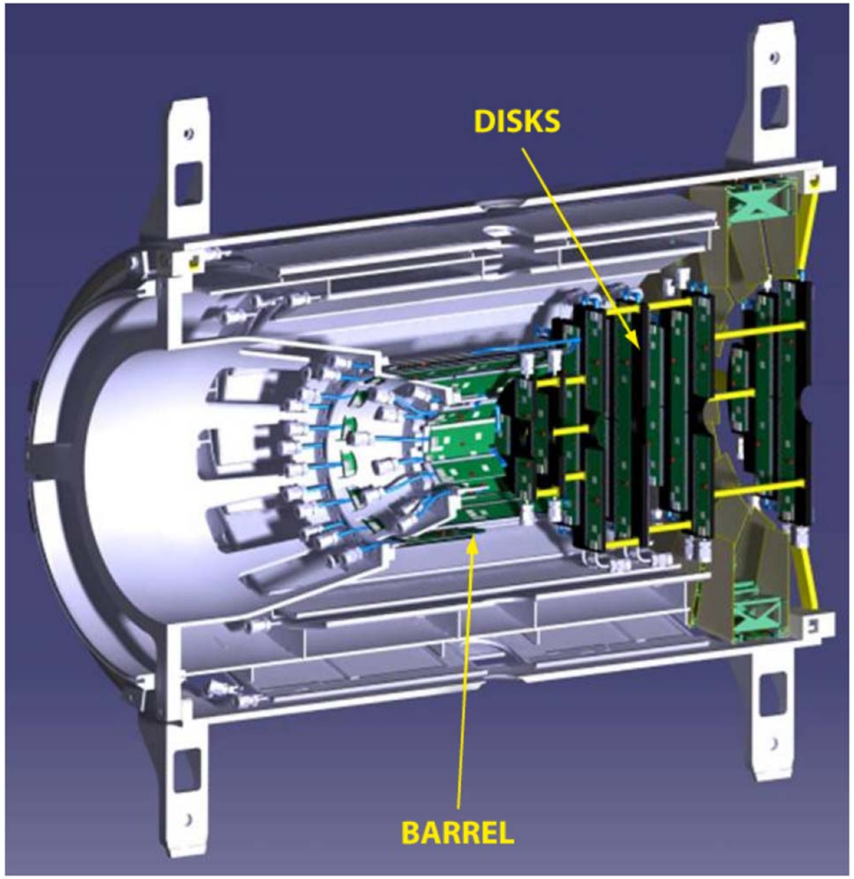


- 4 barrels
  - ✓ *Two inner layers*: hybrid pixel detectors
  - ✓ *Two outer layers*: double side silicon strip detectors
- 6 forward disks
  - ✓ *Four disks*: hybrid pixel detectors
  - ✓ *Last two disks*: mixed pixel and strips

MVD layout







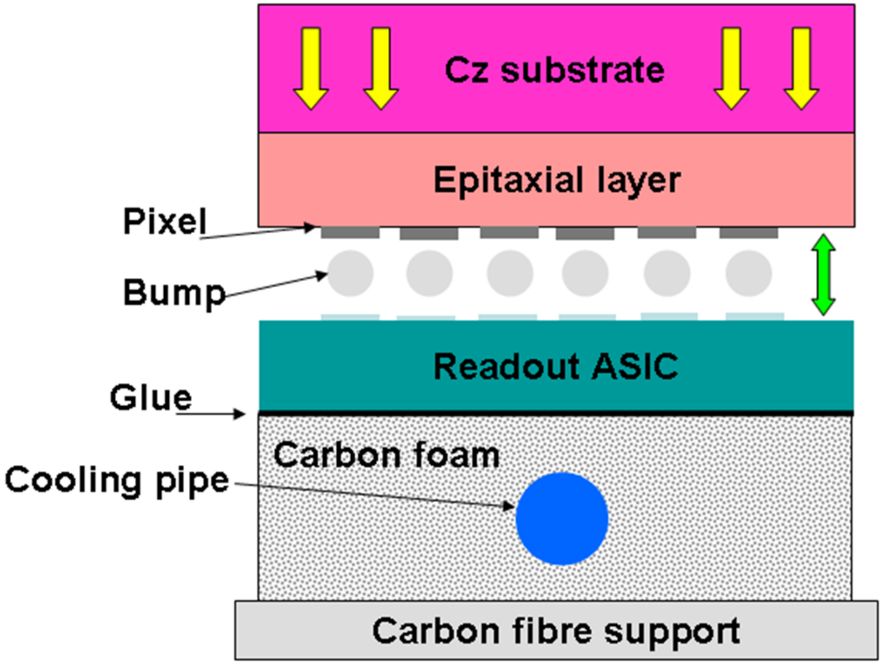
Two halves arranged around the beam-target pipes suspended to the central tracker support

Pixel Detector development

- Custom hybrid pixel
- Pixel detector layout
- Epitaxial silicon sensors
- Readout electronics
- Cooling system based on carbon foam
- Readout architecture
- Aluminum micro strips

Hybrid pixel in PANDA

Thinned pixel sensors



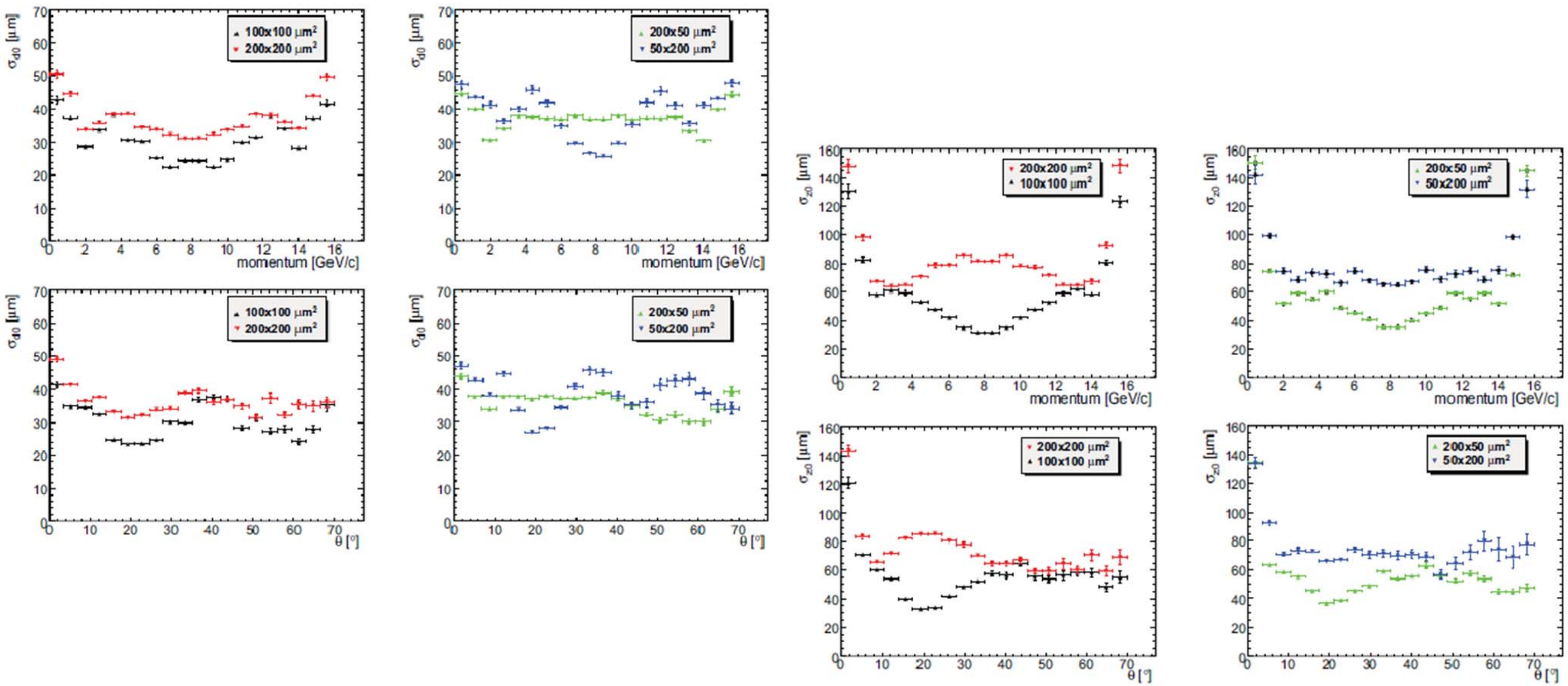
Cz thickness: some hundreds of μm
Resistivity: 0.01-0.02 Ωcm

Epi thickness: 25-150 μm
Resistivity: ~ kΩ cm

Carbon foam with high thermal conductivity

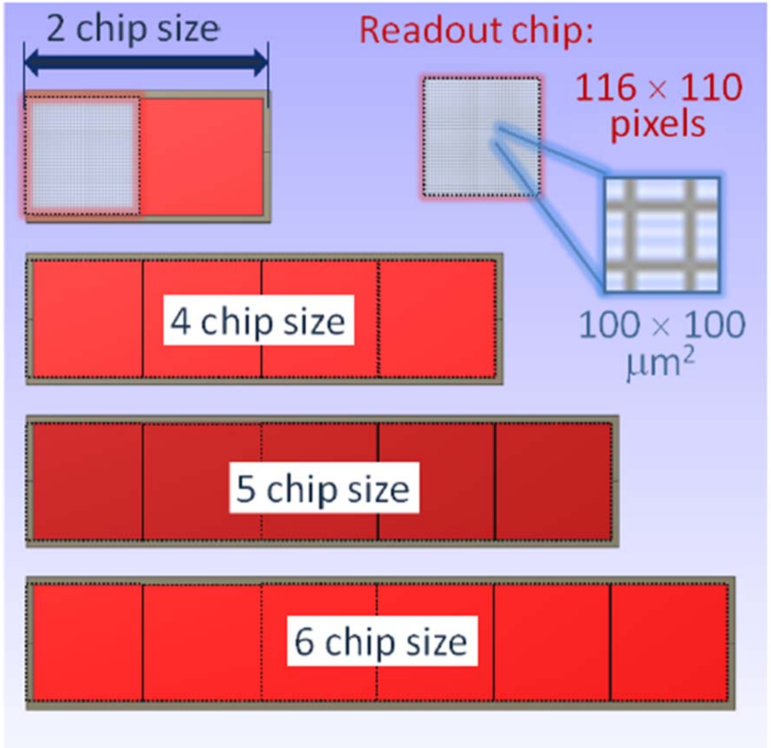
ASIC developed in the 130 nm CMOS technology

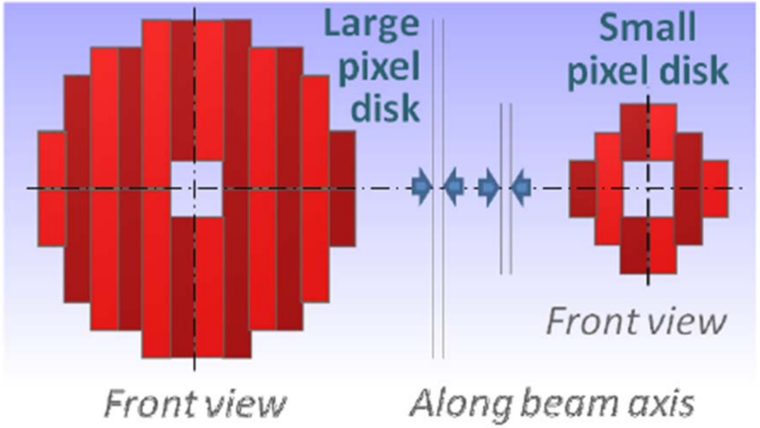
Pixel size choice

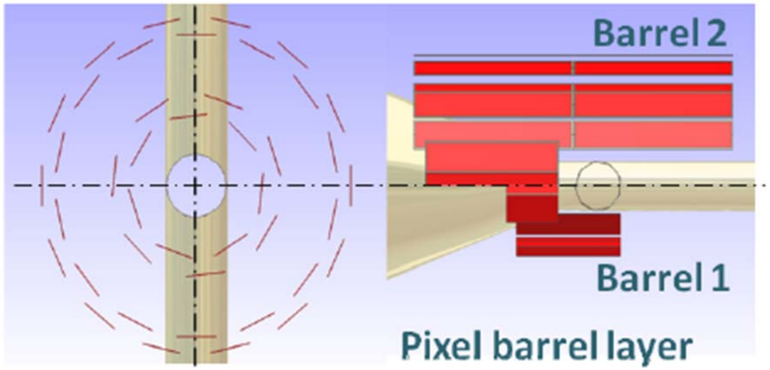


Resolution perpendicular to the beam axis and along the beam axis for the reaction pbar-p-> π+π- @15 GeV/c, as a function of momentum of one of the pions as well as the polar angle

Pixel detector layout



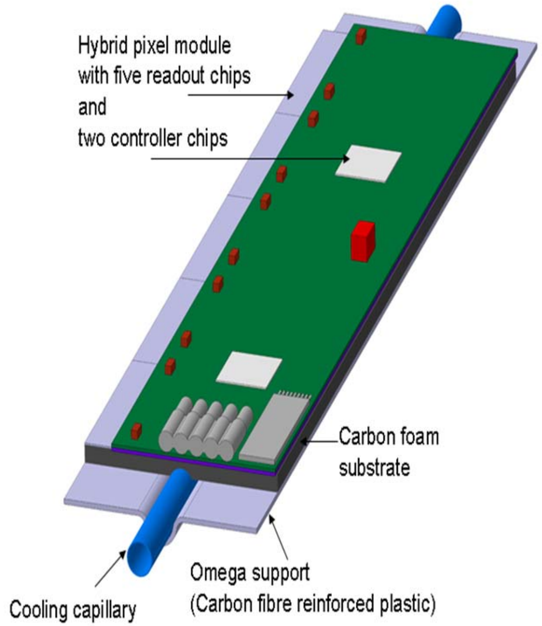


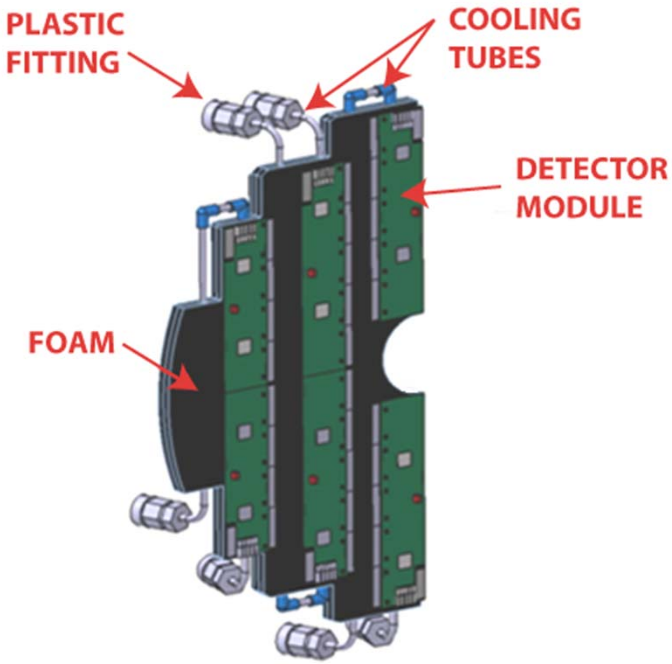


- Layout based on a basic unit corresponding to a readout chip size
- Modules are built by tiling from two to six units
- Size of the basic unit chosen to obtain the best coverage of forward part

176 modules (sensors), 810 readout chips. ~ 10.5 x 10^6 pixels

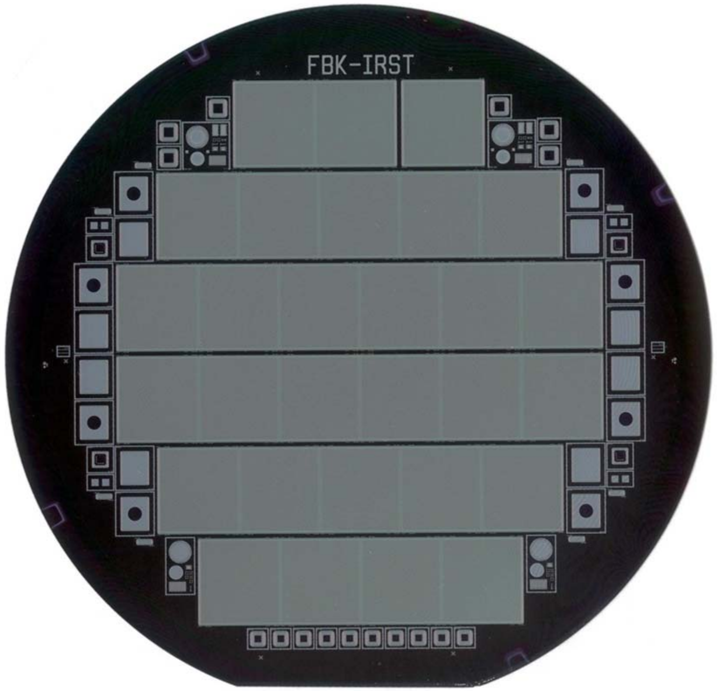
Stave and disk

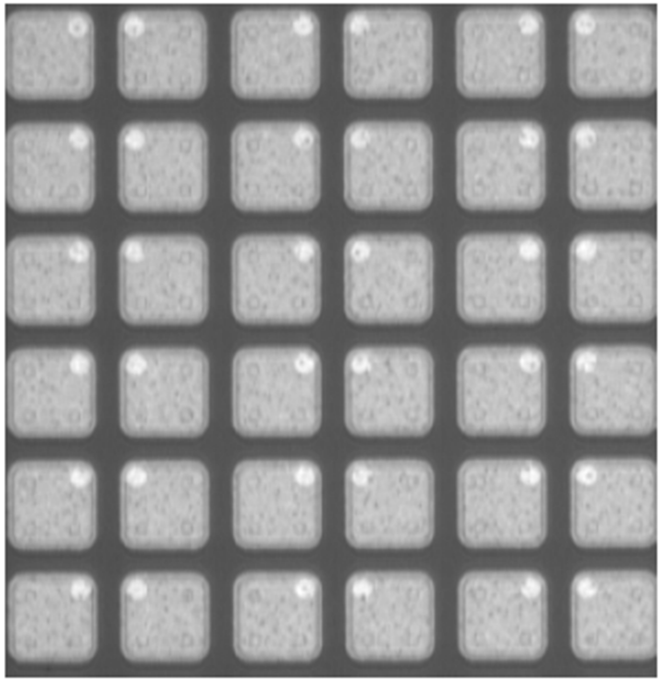




- Disk made of carbon foam, self supporting
- Material to drain heat towards the cooling system: POCO FOAM and POCO HTC
- Embedded cooling capillary in the carbon foam plate
- Modules glued with thermal glue

Epitaxial silicon sensors



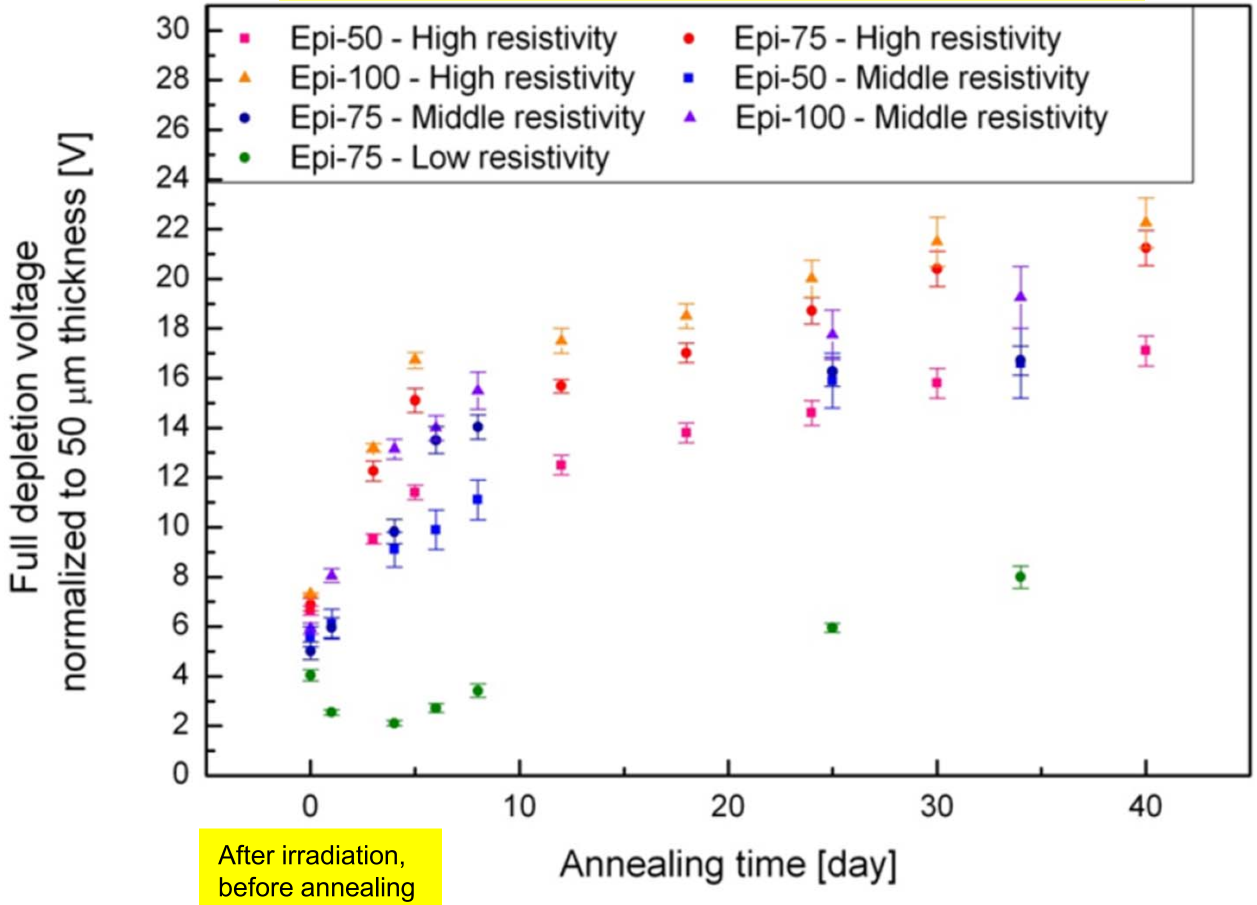


Pad layout matching the double column readout

- 4 " raw wafer provided by ITME (Varsaw) with epi n/P and Cz n+/Sb, processed by FBK (Trento) to obtain pixel p in n
- Thinning process tested up to ~100 μm (@ VTT, WaferS)
- Several epi-thickness and epi-resistivity tested
- Radiation tolerance studied with neutrons from reactor

Campaign of radiation damage test with neutrons

Fluence of ~ 1.5 x 10 ^{14} 1 MeV equivalent n/cm^2



After irradiation, before annealing

Epi-50, HR: 49 µm (4.1 kΩ·cm,)
Epi-75, HR: 74 µm (4.6 kΩ·cm,)
Epi-100, HR: 98 µm (4.9 kΩ·cm)
Epi-50, MR: 50 µm (3.1 kΩ·cm)
Epi-75, MR: 75 µm (3.2 kΩ·cm)
Epi-100,MR: 100 µm (3.6 kΩ·cm,)
Epi-75, LR: 75 µm (0.5 Ω·cm)
+ Cz substrate (0.01-0.02 Ω·cm)

- Extrapolated leakage current < 20 nA/pixel (100 µm x 100µm size, 100 µm thick), immediately after the irradiation.
- It decreases by a factor 2 after some days of annealing at 60°C

Pixel electronics requirements

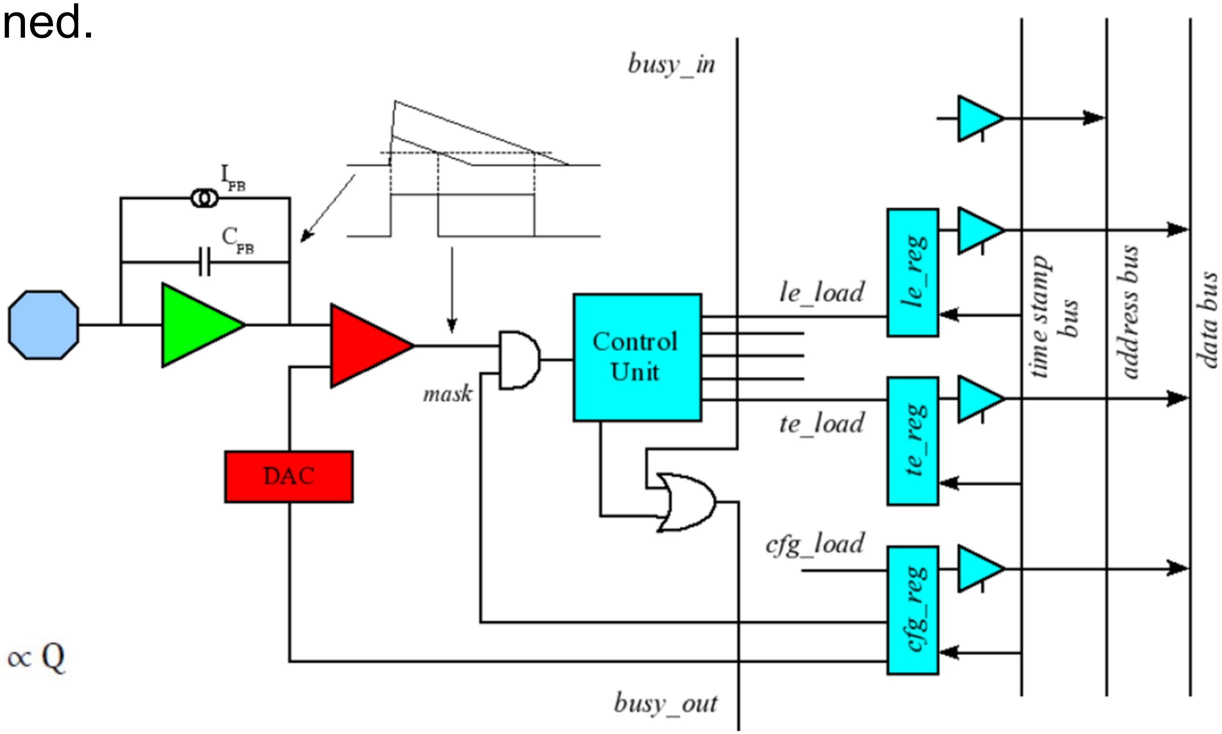
Pixel size	100 μm x 100 μm
Self trigger capabilities	
Chip active area	11.4 mm x 11.6 mm
Noise floor	< 0.032 fC
Dynamic range	12 bits
Time resolution	6.5 ns
System clock	155.52 MHz
Power consumption	< 1 W/cm^2
Total ionizing dose	< 10 Mrad
1 MeV equivalent neutron	10^{14} /cm^2

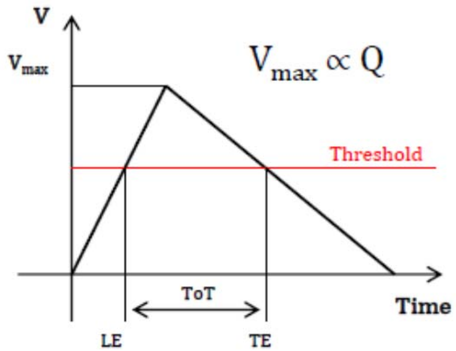
- Technology for the front-end ASIC: 130 nm CMOS
- Charge encoding with Time over Threshold (ToT) technique
- Data rate per chip up to ~ 450 Mb/s

Pixel architecture

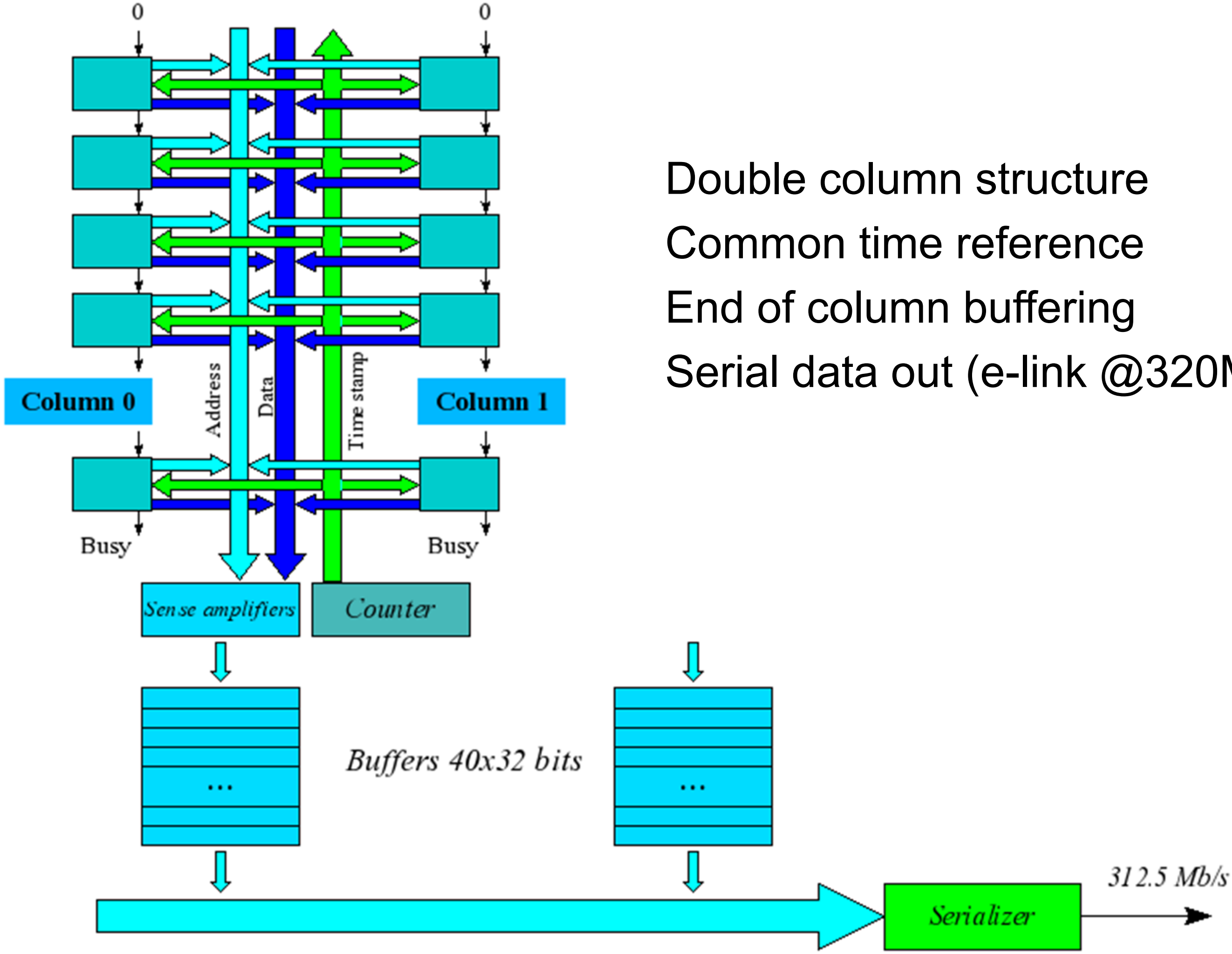
- Initial thoughts based on use of ATLAS FEI3.
- Several constraints (pixel size, triggerless request) pushed to an 'ad hoc' development even if interesting FEI3 features have been retained.

1. Internal calibration circuit
2. CSA
3. Constant current feedback
4. Leakage compensation (up to 50 nA/pixel)
5. DAC
6. Comparator
7. Clipping circuit





Column readout architecture



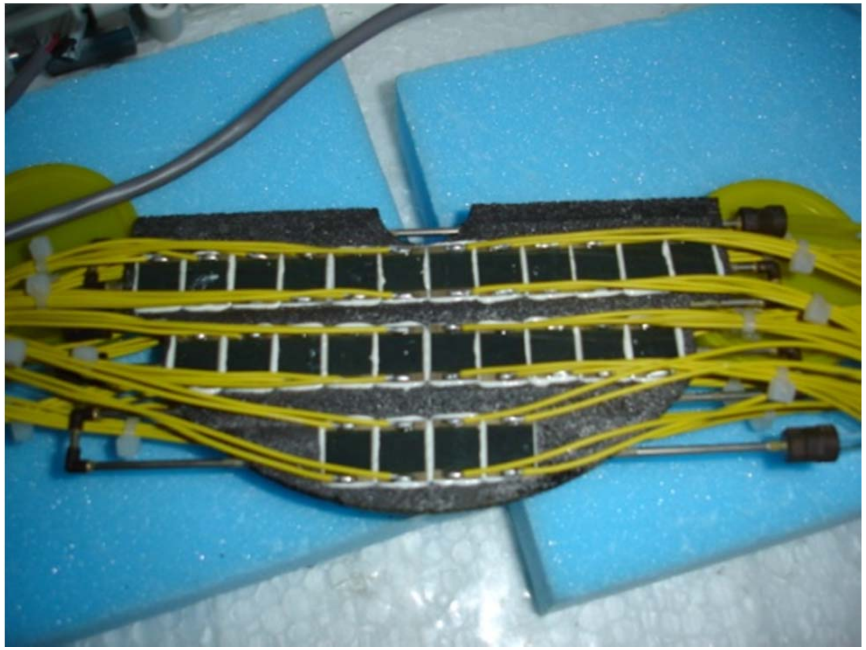
Double column structure

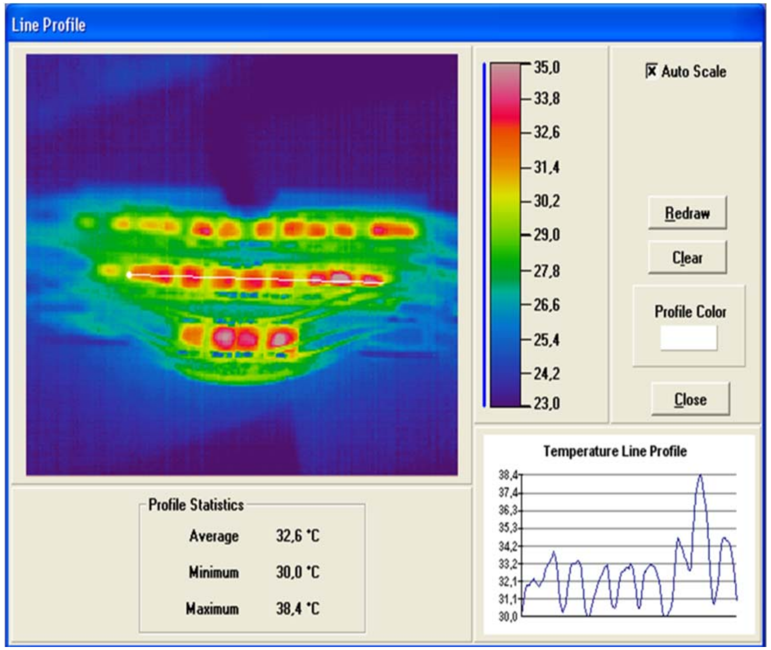
Common time reference

End of column buffering

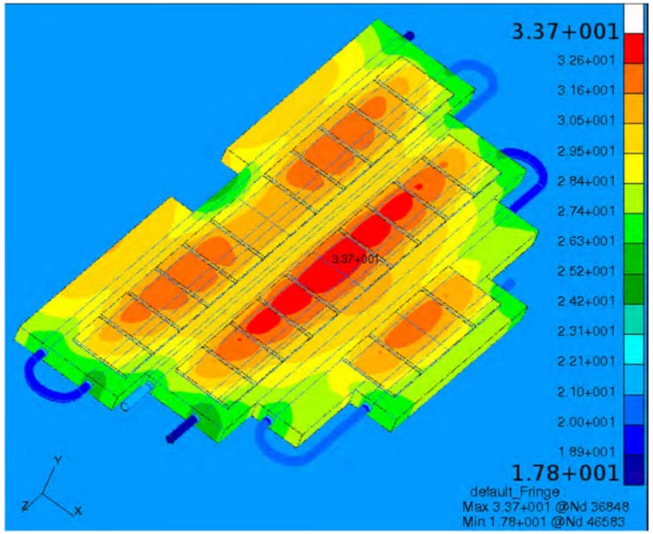
Serial data out (e-link @320Mb/s), SLVS I/O

Cooling system

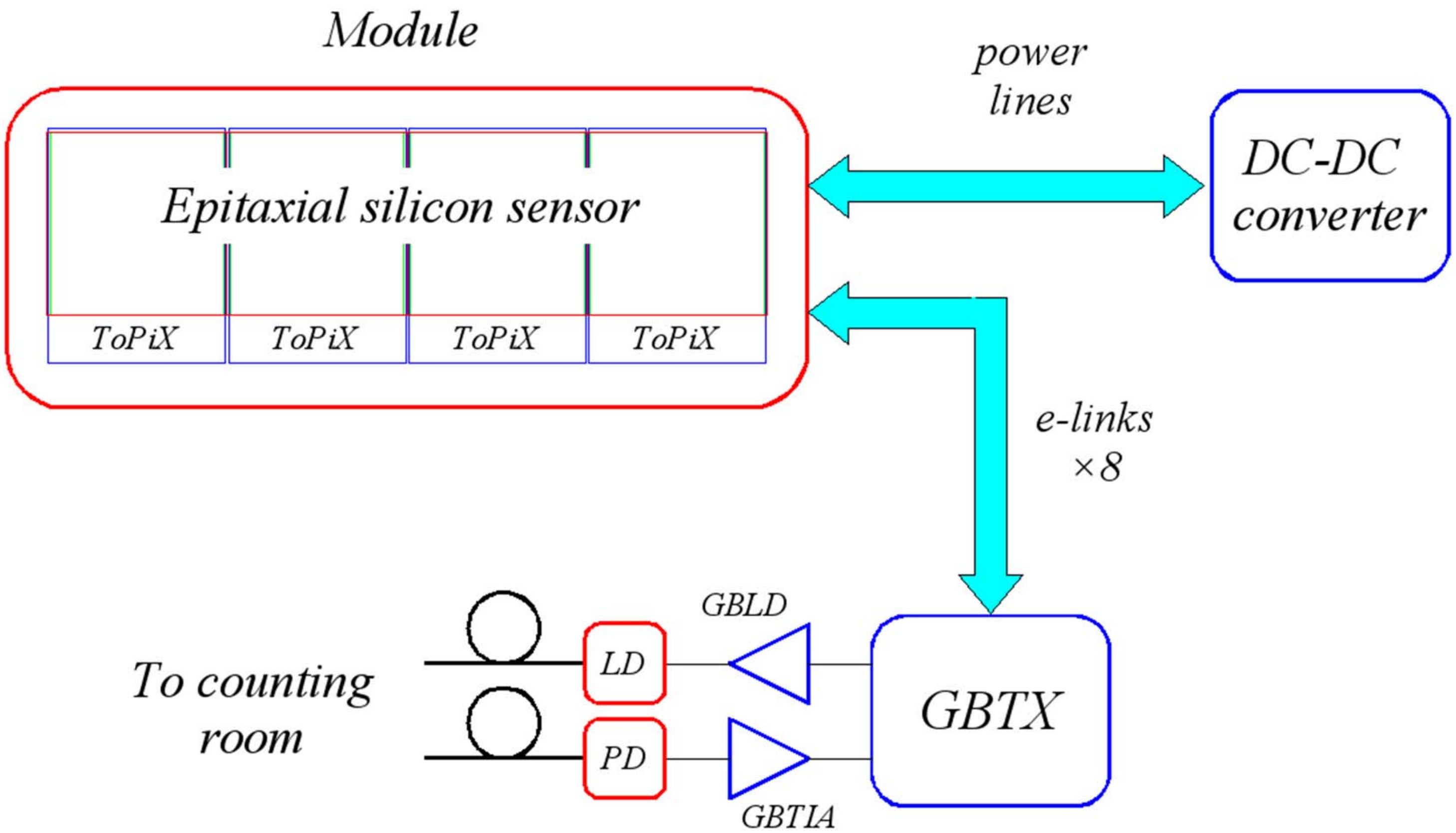




- Total power 94 W
- Cooling pipe diameter 2 mm (MPN35N Ni-Co alloy)
- 4 mm carbon foam
- Cooling flow 0,3 l/m, inlet temperature: 18.5 °C
- HTC thermal conductivity = 50 W/m·K



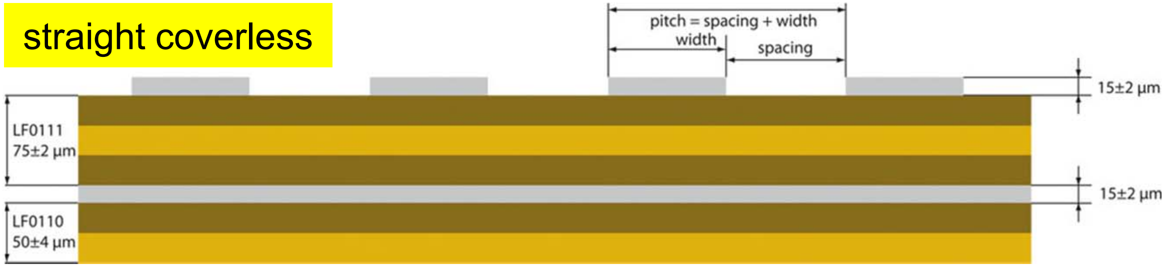
Readout architecture

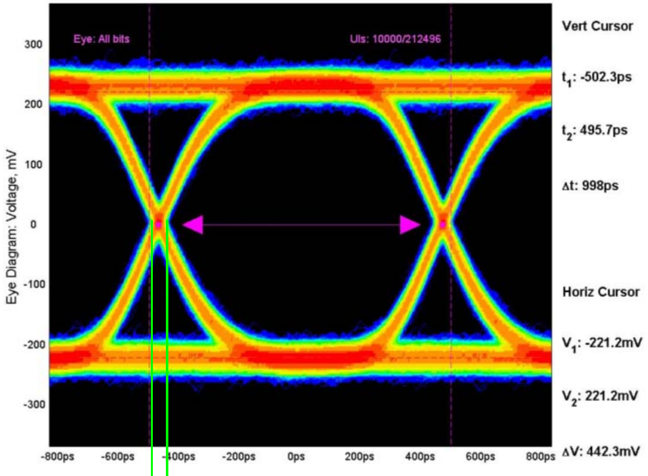


Signal transmission

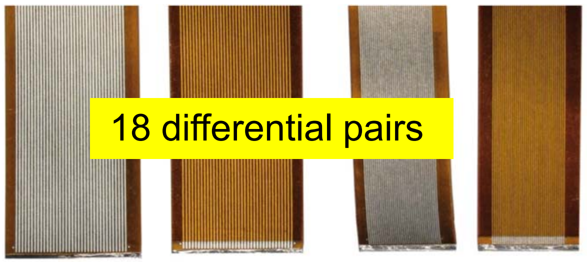
1 m long aluminum strips prototypes

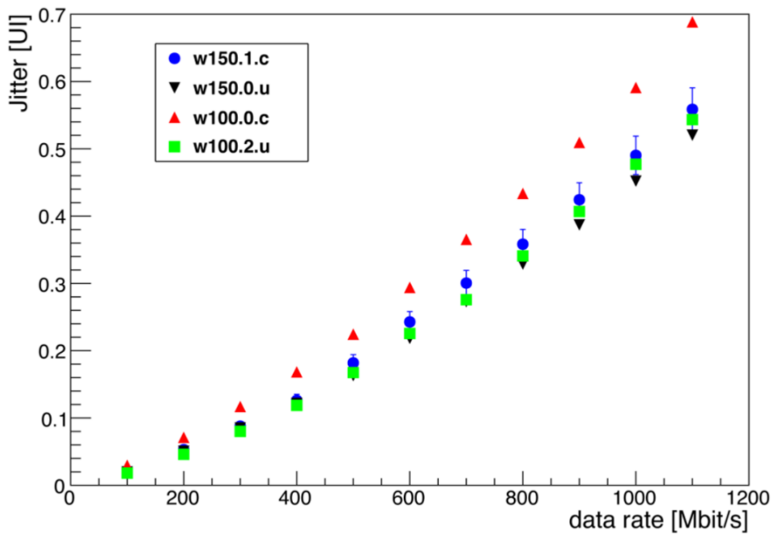
straight coverless





Technology based on laminated aluminum on kapton, reliable for bonding, produced @ CERN according to our design



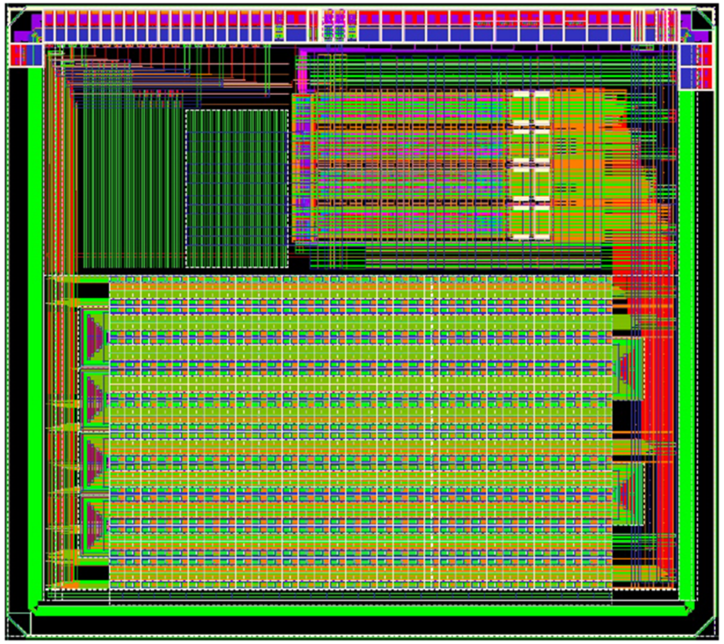


Prototyping and first results

- Single chip assembly
- Validation of the triggerless readout

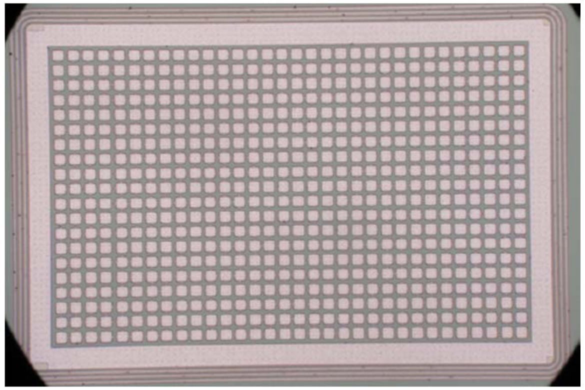
Prototyping

- Small prototypes with MPW to address relevant issues
- Third readout generation prototype contains all the relevant features
  - Folded columns to combine realistic column length (data transmission issues) with acceptable chip form factor, made of:
    - 2 long columns of 128 pixels
    - 2 short columns with 32 pixels as reference
  - Triple redundancy-based SEU protection (register)
  - Serial ouput and SLVS I/O
  - Connection to a custom sensor

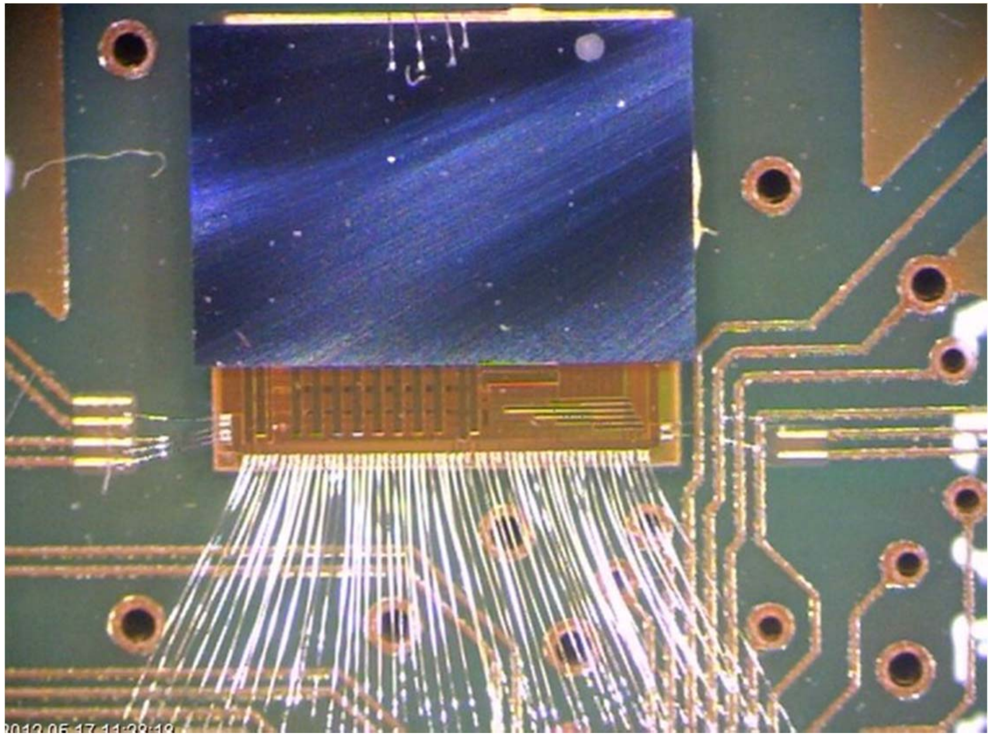


ToPix_3

640 pixel sensor



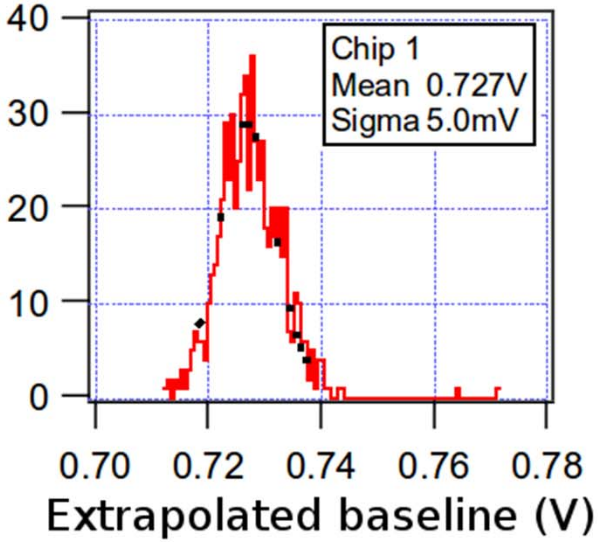
Single chip assembly

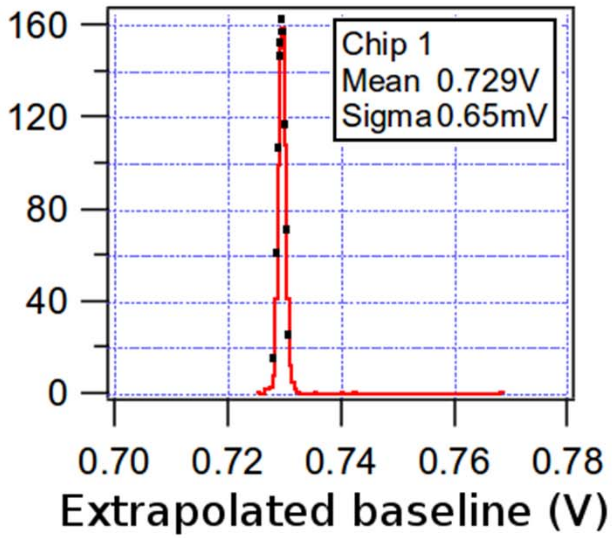


- ToPix_3 prototype and the custom epitaxial sensor.
- Cz thinning + Bump bonding @ IZM (Berlin) using Sn-Pb bumps.
  Yield of the tested assemblies : ~ 99.5 %
- The thin Cz layer is the ohmic contact for the sensor biasing.
- Dedicated testing board.

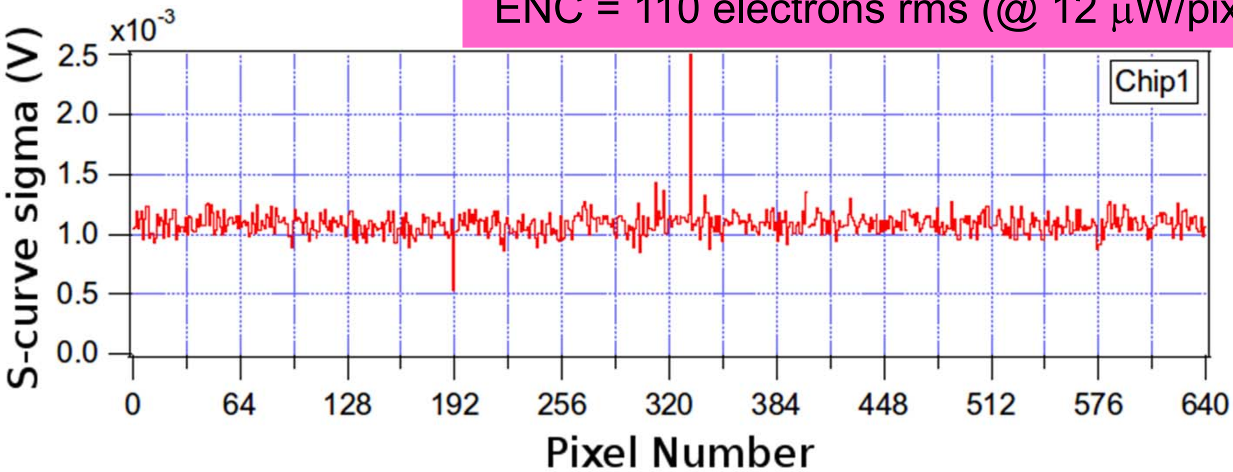
Baseline and noise

~ 62 electrons

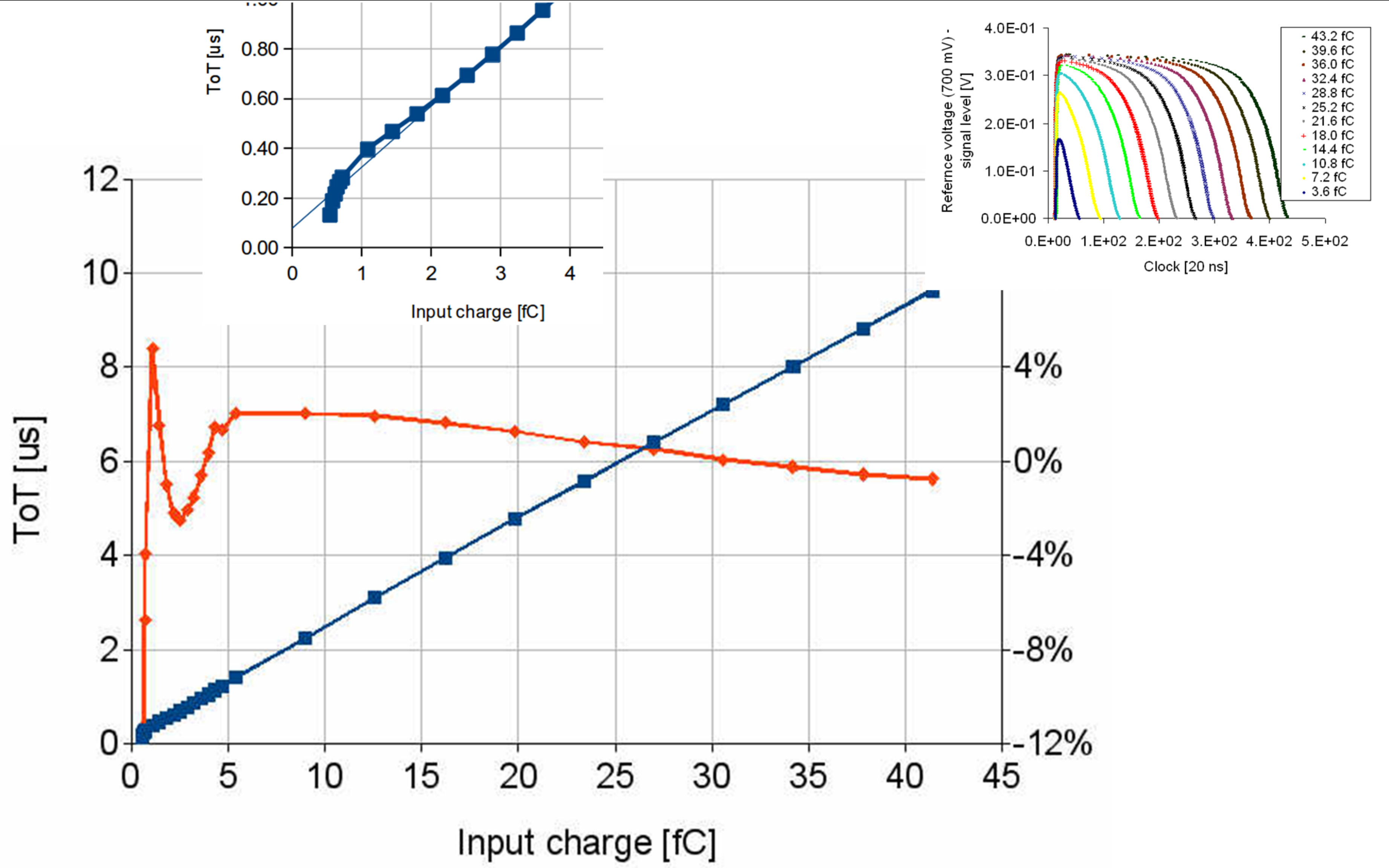




ENC = 110 electrons rms (@ 12 μW/pixel)

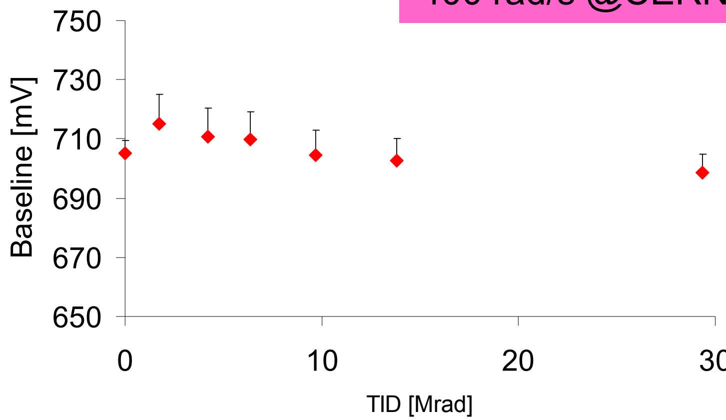


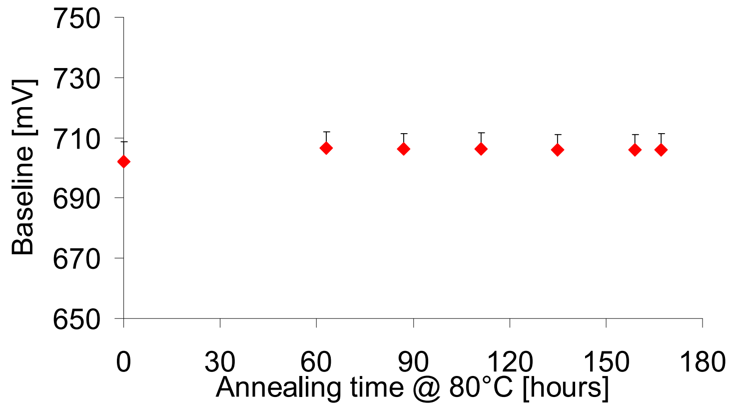
Time over Threshold linearity

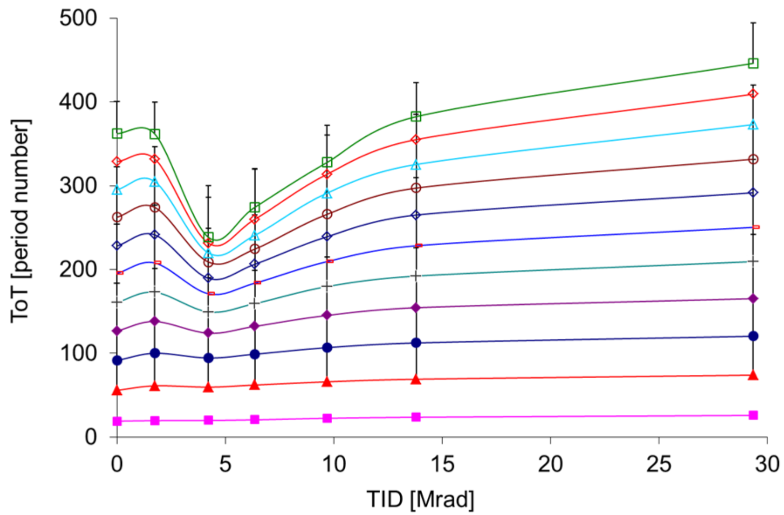


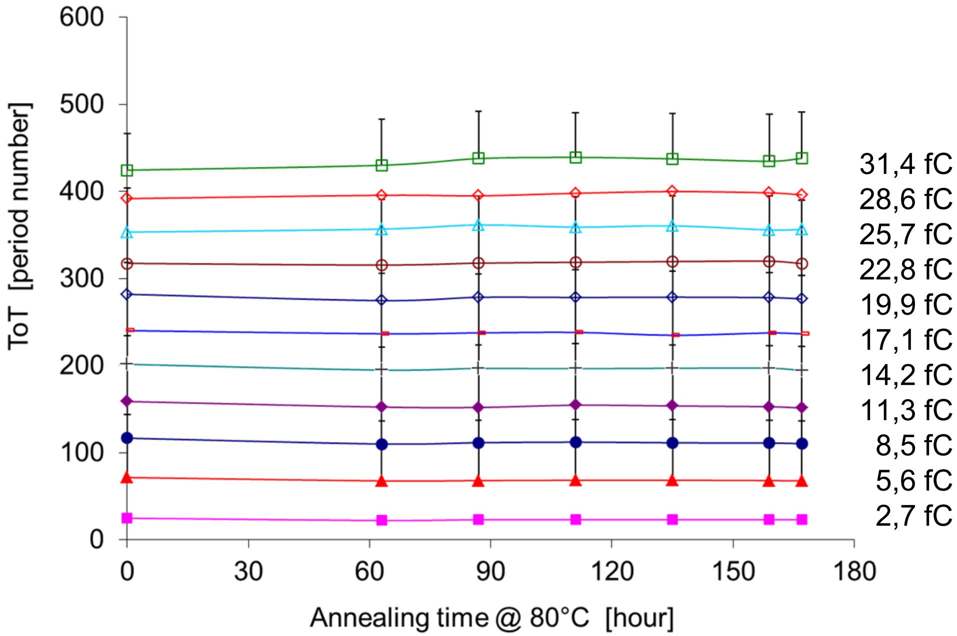
Total Ionizing Dose

400 rad/s @CERN







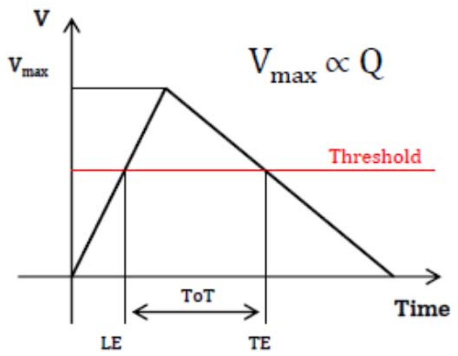


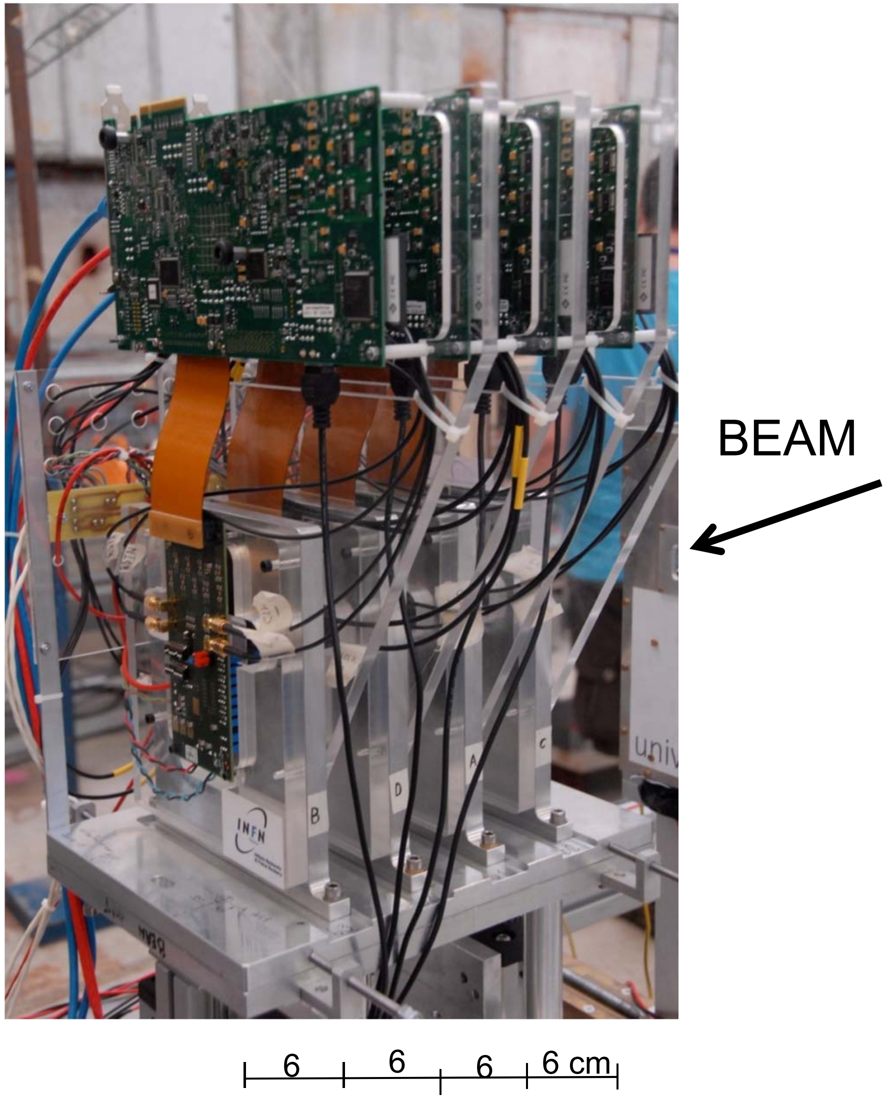
Pixel tracking station

Pixel raw data:

- ❑ Column & row information
- ❑ Timestamp
- ❑ (Leading Edge) + Trailing Edge (Gray encoded)

each hit



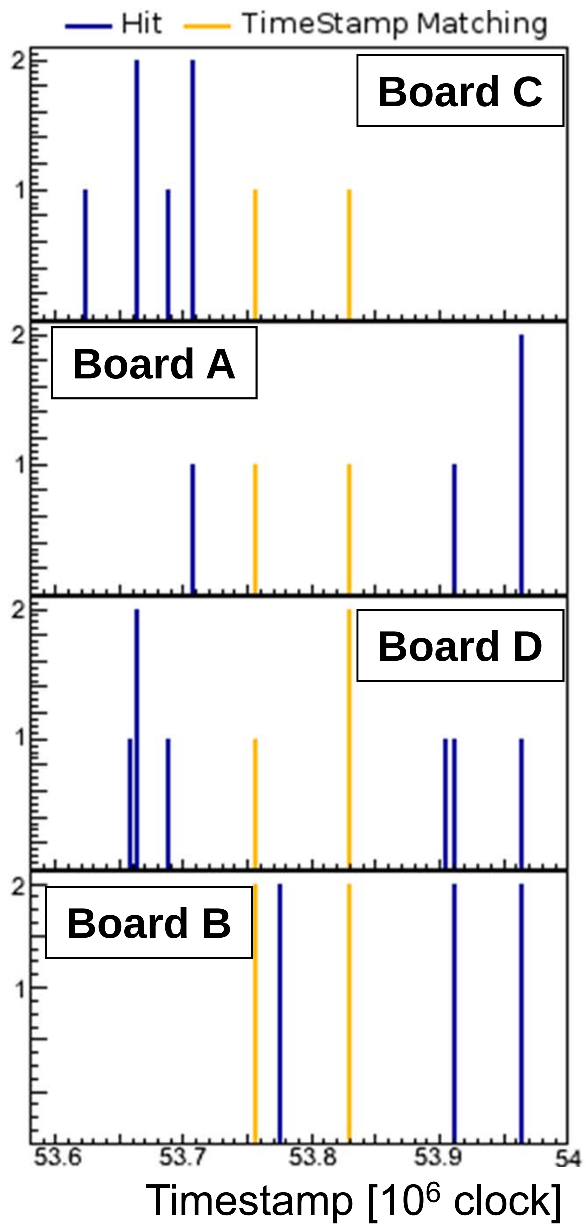


Time stamp matching I

Raw Data → Pixel Hit → TimeStamp Matching → PandaRoot

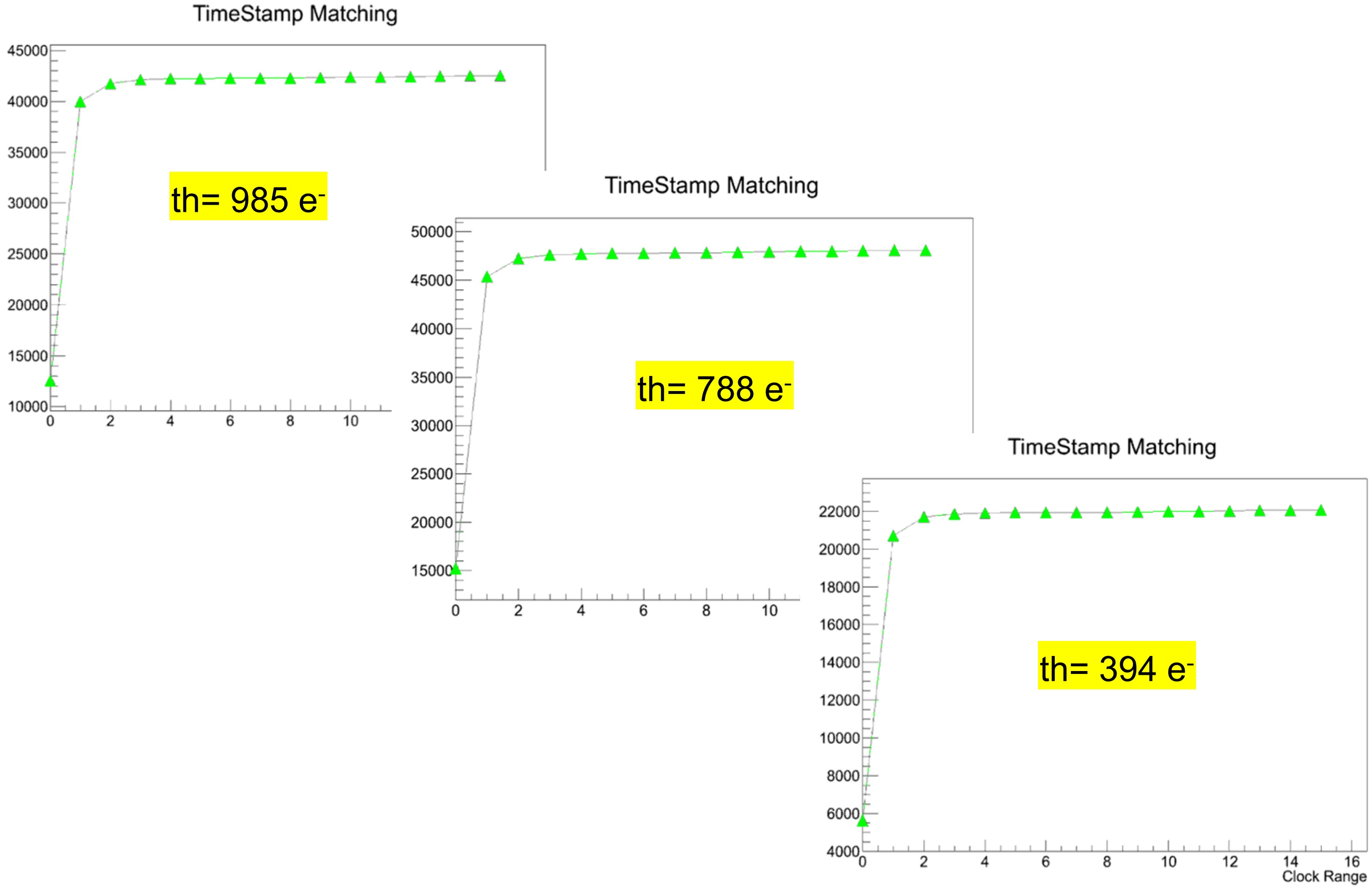
BOARD0		BOARD1		BOARD2		BOARD3	
Row	fTimeStam	Row	fTimeStam	Row	fTimeStam	Row	fTimeStam
210	537020249	150	558724657	190	546305718	155	558729325
211	546462082	151	558730152	191	546305718	156	558730152
212	558710073	152	558733717	192	546305718	157	558732955
213	558724656	153	558739485	193	558704130	158	558733716
214	558730152	154	558748899	194	558730151	159	558738431
215	558742175	155	558749613	195	558732954	160	558738432
216	558749612	156	558755429	196	558733718	161	558739485
217	558749615	157	558762802	197	558733720	162	558743179
218	558755430	158	558765329	198	558738431	163	558745417
219	558762802	159	558766188	199	558739485	164	558748900
220	558765330	160	558766254	200	558748900	165	558749612
221	558766189	161	558766528	201	558749612	166	558754553
222	558766253	162	558766529	202	558753162	167	558755429
223	558766674	163	558768586	203	558754310	168	558762802
224	558770175	164	558770174	204	558755429	169	558765330
225	558770402	165	558770174	205	558762802	170	558766188
226	558770904	166	558770402	206	558765330	171	558766254
227	558775489	167	558770903	207	558766188	172	558766419
228	558781647	168	558775489	208	558766253	173	558768586
229	558781648	169	558781647	209	558766528	174	558769056
230	558786946	170	558781649	210	558766531	175	558770174
231	559024129	171	558786945	211	558768586	176	558770904
232	559028535	172	559024127	212	558770174	177	558775489
233	559031646	173	559028535	213	558770904	178	558781015
234	559032975	174	559028891	214	558770904	179	558781225

44 bit timestamp = 32 bit EOC + 12 bit Leading edge



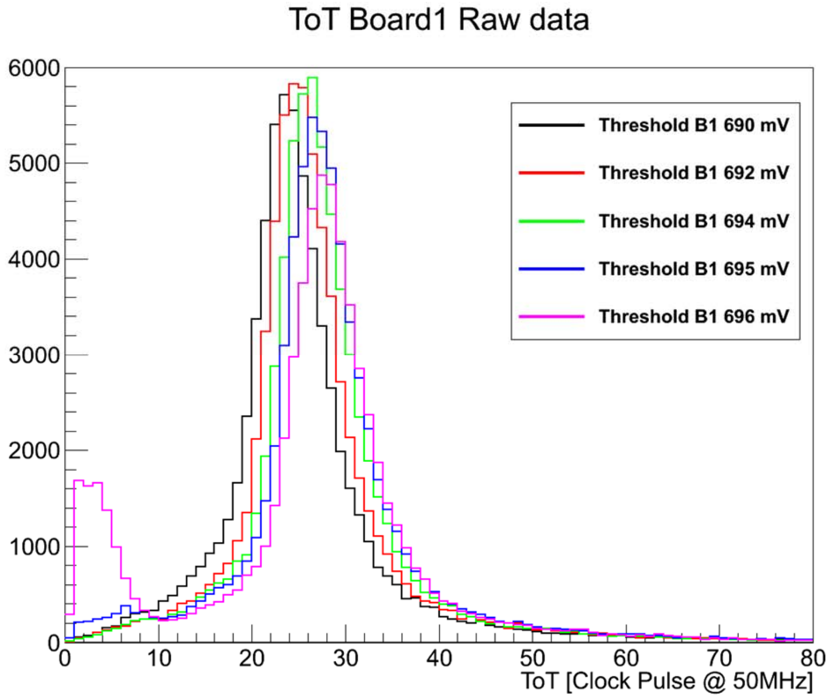
Clock @ 50 MHz

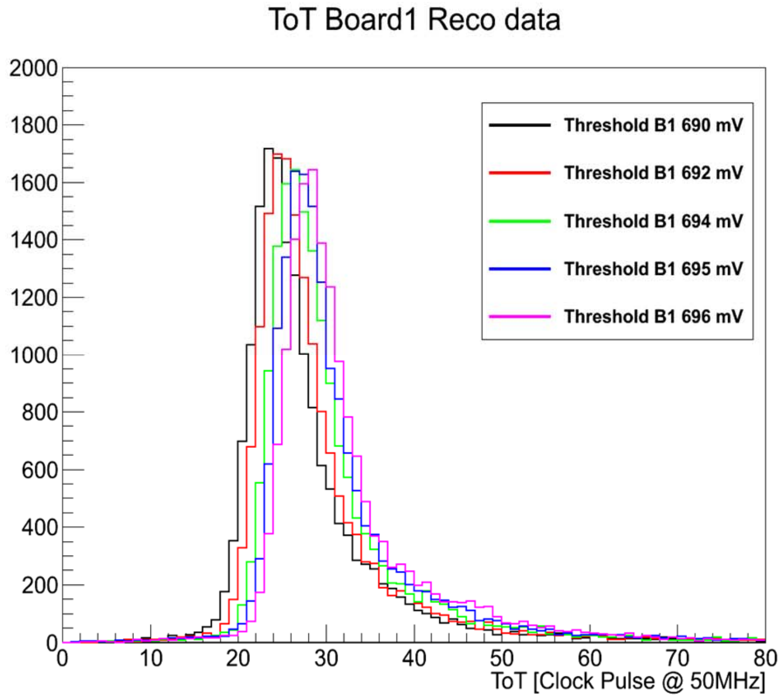
Time stamp matching II



- Time stamp matching number vs the clock window (clock @ 50 MHz)
- 3 different thresholds

ToT distributions



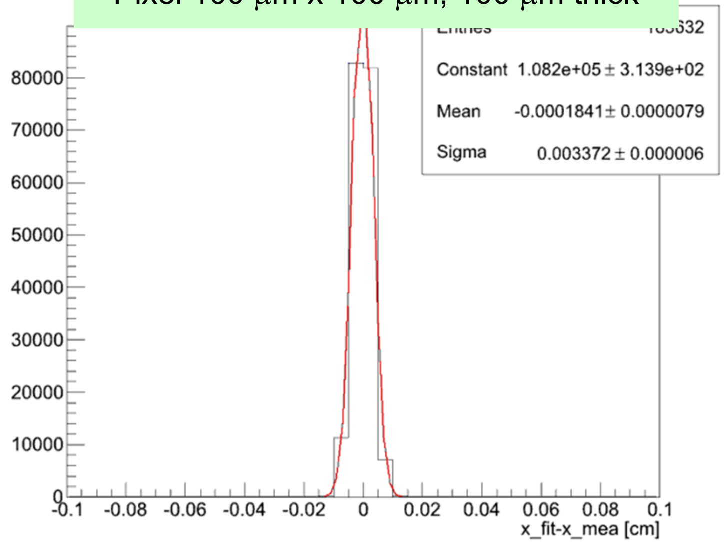


- From raw data to reconstructed tracks
- Fit with a Landau-Gaussian convolution

Results overview

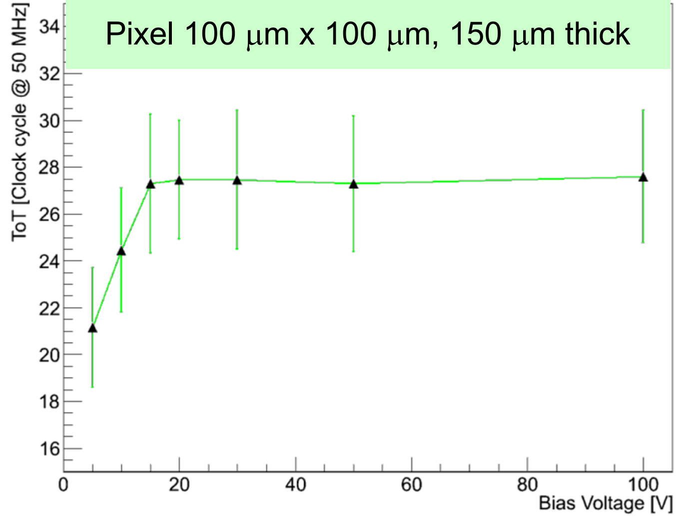
Residual distribution

Pixel 100 μm x 100 μm, 100 μm thick



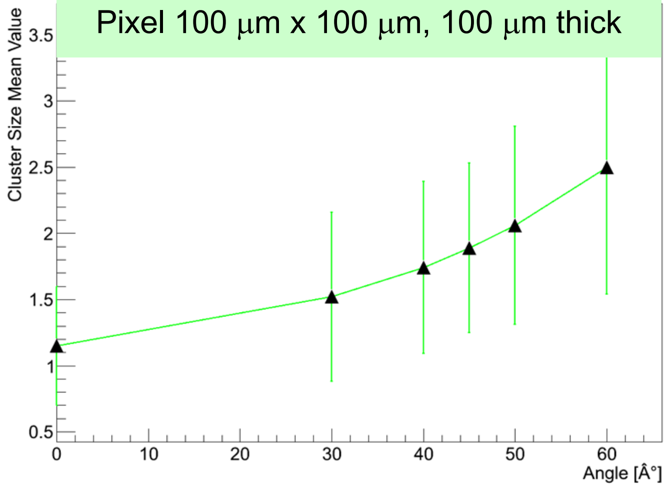
ToT vs sensor bias

Pixel 100 μm x 100 μm, 150 μm thick



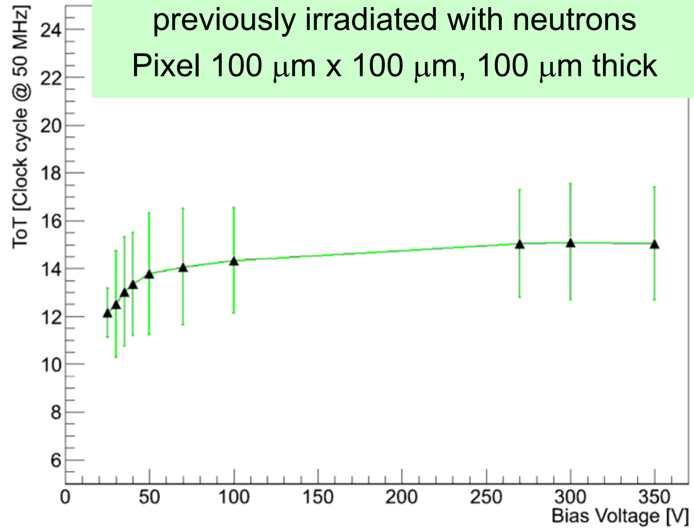
Cluster size vs angle

Pixel 100 μm x 100 μm, 100 μm thick



ToT vs sensor bias, assembly previously irradiated with neutrons

Pixel 100 μm x 100 μm, 100 μm thick

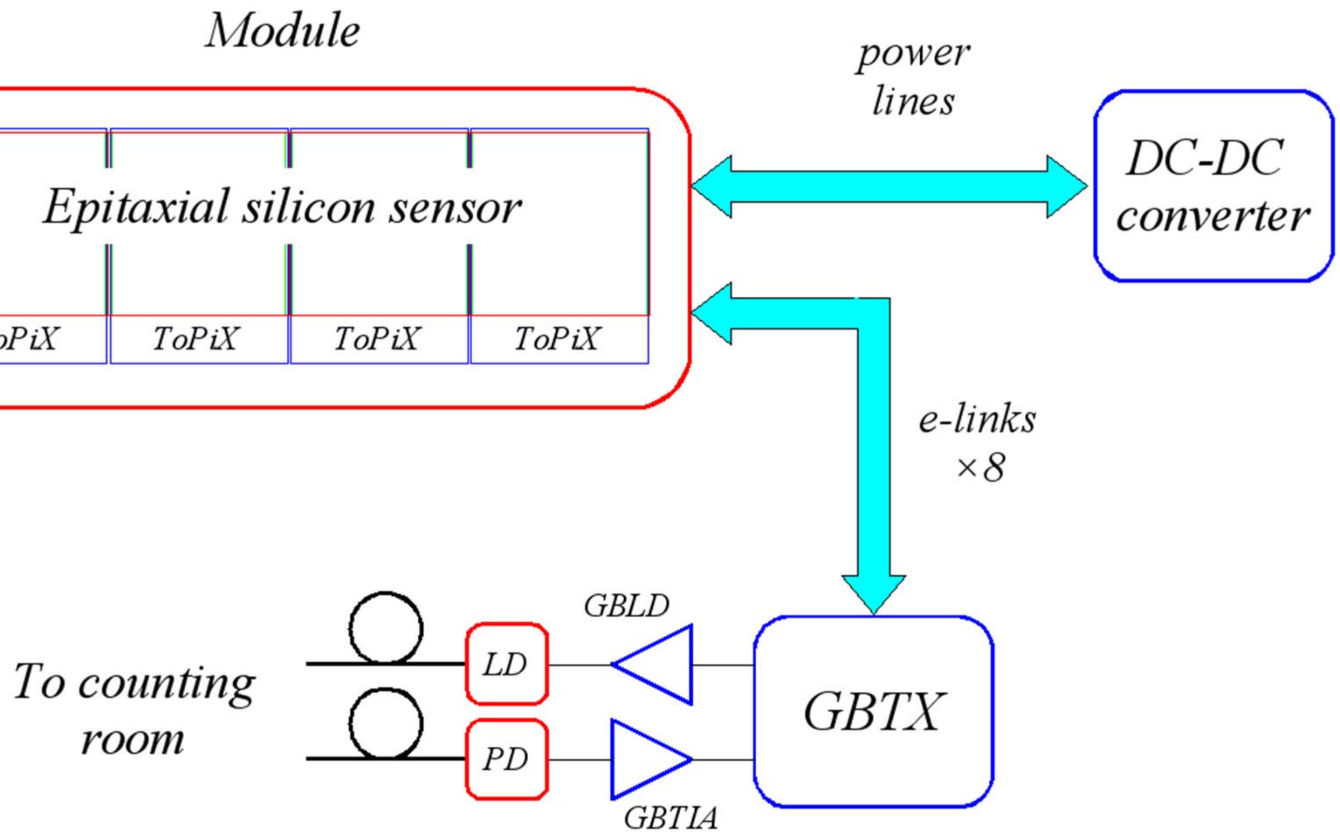


Conclusions

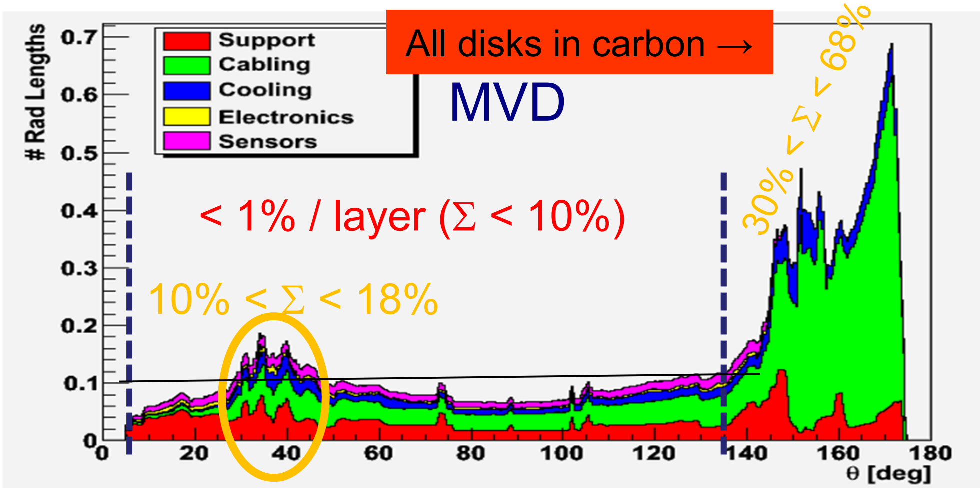
- The goal to extend our knowledge in the field of the physics push to
  - ✓ precise measurements
  - ✓ new electronics / detector developments
  - ✓ new acquisition method and analysis

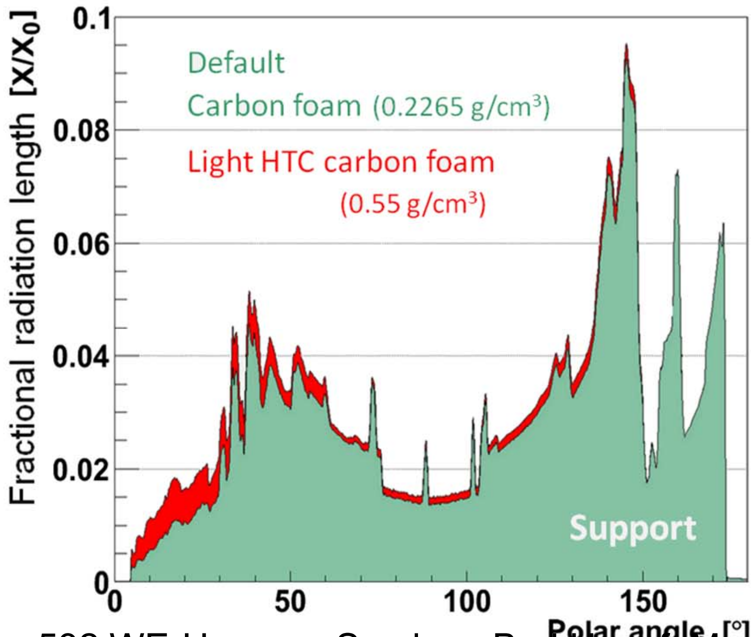
- All these items have been pursued and are ongoing with the pixel detector of PANDA and not only there !!!

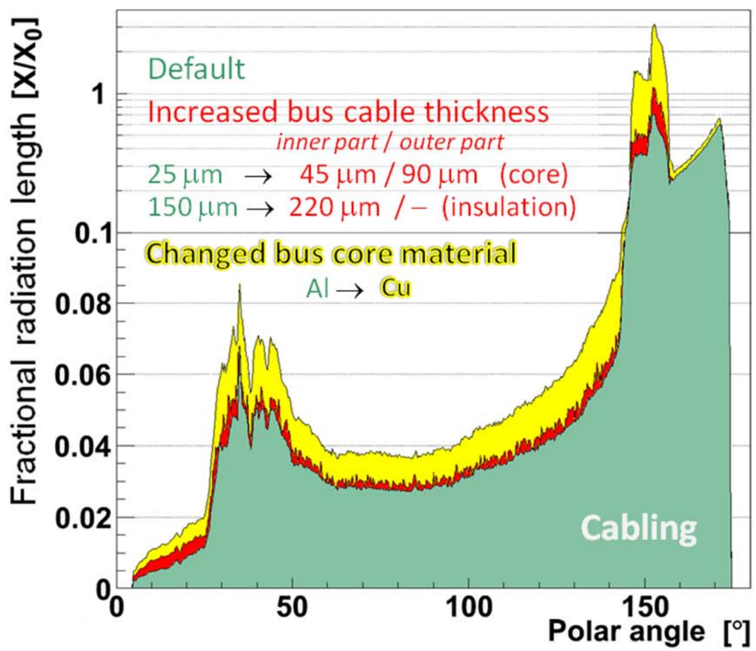
Readout architecture



Radiation length studies

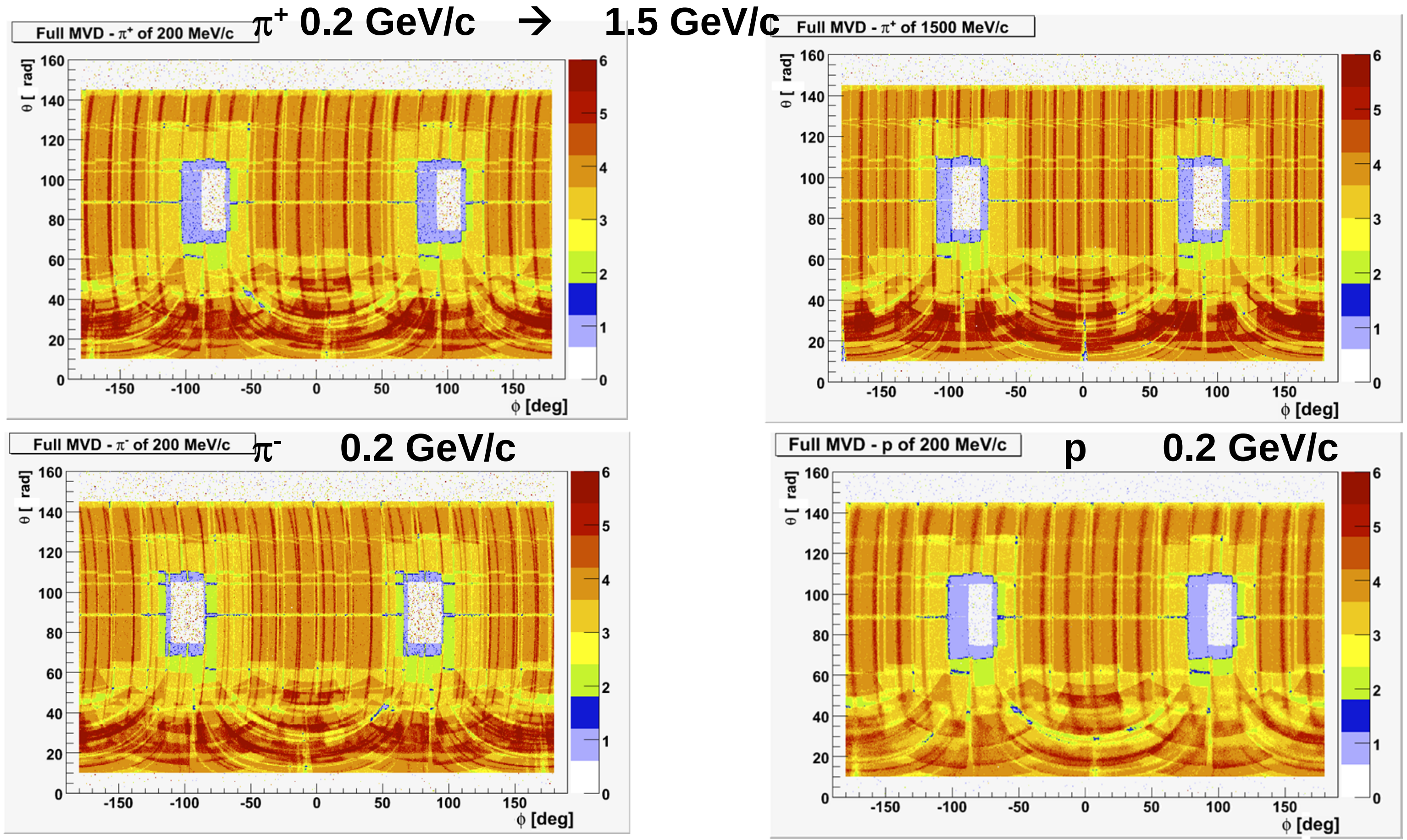






D. Calvo, 532 WE-Haereus-Seminar, Bad Honef, May 24, 2013

MVD coverage

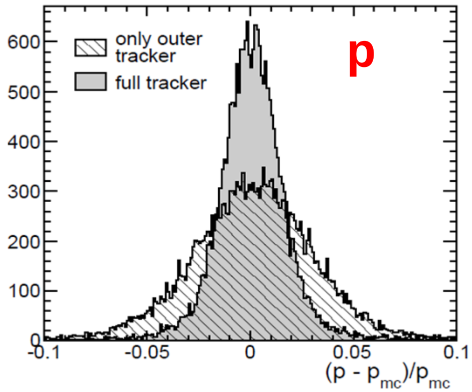


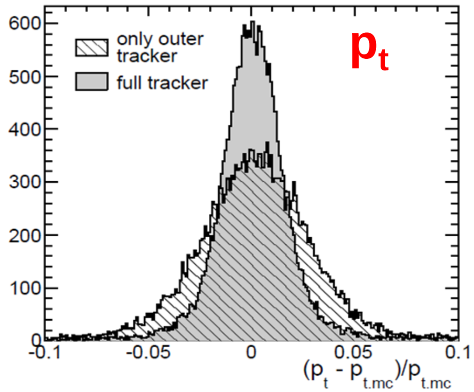
- The design is optimized to obtain 4 MVD hit points per track
- Plots show the spatial distribution of the number of hit points in the MVD
- Particles were shot from the vertex (0;0;0)
- Coverage studies with several particles species and different momenta

Performance I

Momentum resolution

1 GeV/c π





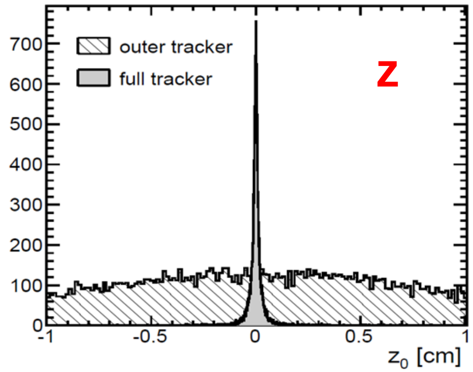
$\sigma(p)$ without MVD = 2.6 %
$\sigma(p)$ with MVD = 1.4 %

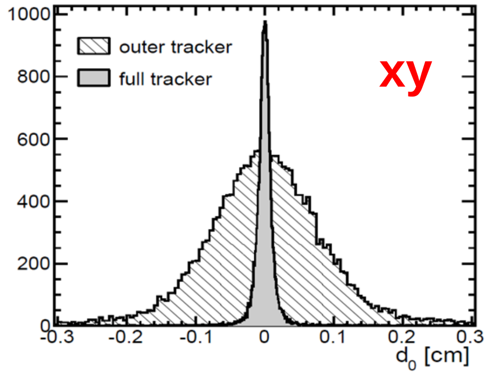
$\sigma(p_t)$ without MVD = 2.9 %
$\sigma(p_t)$ with MVD = 1.4 %

→ Improvement by 50%

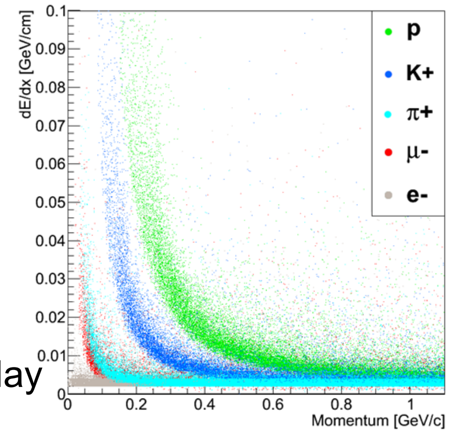
Single track resolution

→ No resolution along z without MVD



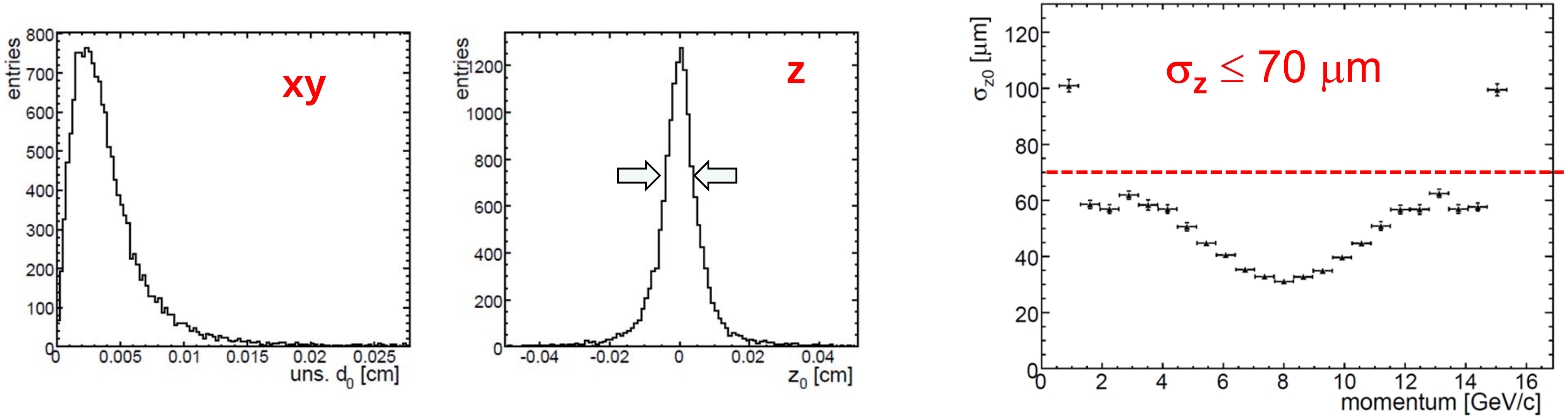


Energy loss information



Performance II

Primary vertex resolution $\bar{p}p \to \pi^+\pi^-$ 15 GeV/c

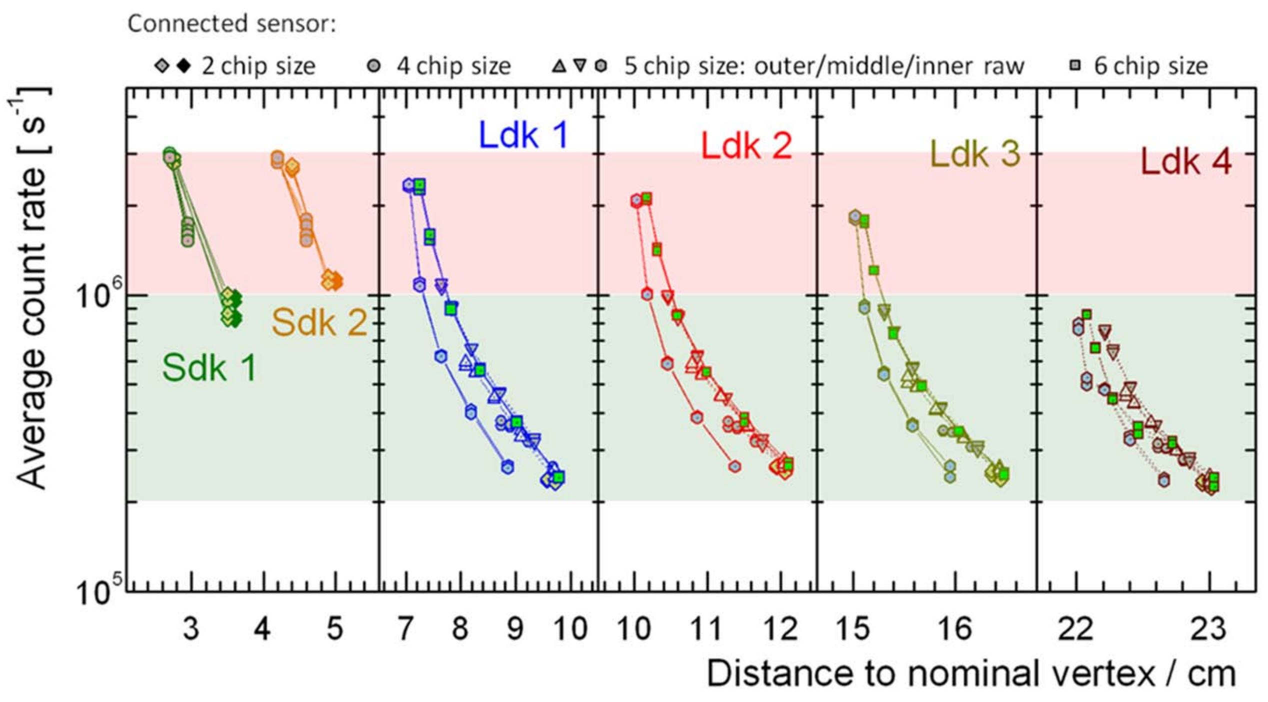


Vertex resolution $\bar{p}p \to D^+D^-$ (6.57 / 7.50 / 8.50) GeV/c

momentum GeV/c	vertex resolution [µm] primary			secondary		
	$\sigma_{prim,x}$	$\sigma_{prim,y}$	$\sigma_{prim,z}$	$\sigma_{sec,x}$	$\sigma_{sec,y}$	$\sigma_{sec,z}$
6.57	30.7	30.7	493.6	35.4	35.2	77.1
7.50	30.4	30.3	208.5	37.1	36.4	84.0
8.50	30.0	29.0	157.4	36.7	36.2	92.4

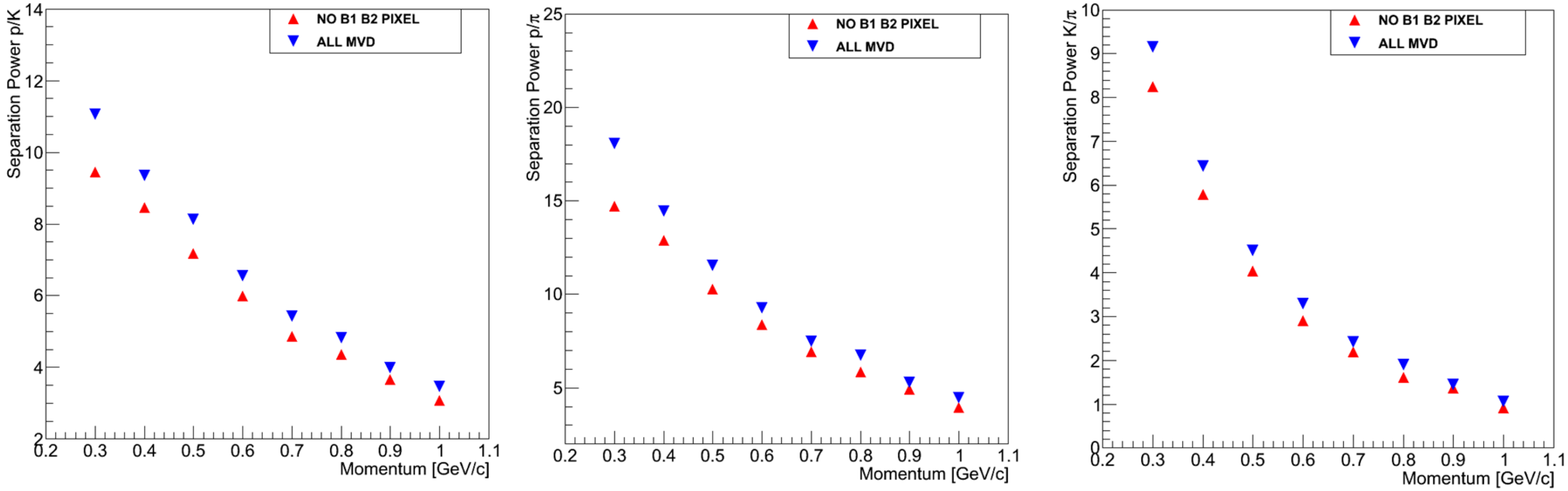
→ Secondary vertex resolution:
$\sigma_{x,y} \leq 35$ µm
$\sigma_z \leq 100$ µm

Rate



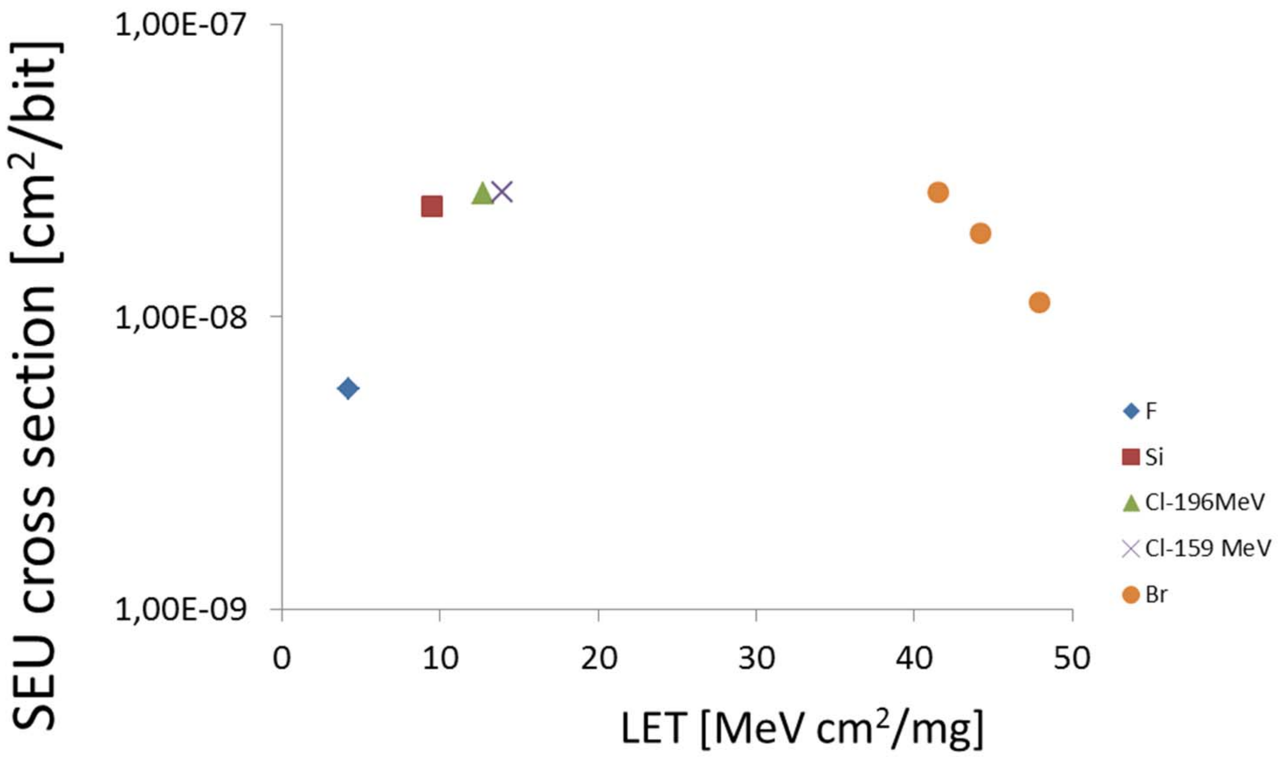
Connected sensor:
2 chip size
4 chip size
5 chip size: outer/middle/inner raw
6 chip size
Average count rate [s^{-1}]
10^6
10^5
Sdk 1
Sdk 2
Ldk 1
Ldk 2
Ldk 3
Ldk 4
3
4
5
7
8
9
10
10
11
12
15
16
22
23
Distance to nominal vertex / cm

Separation power



- Separation power in the angular range 50°-110° - barrrel part
- 3 different pairs of particle species

Single event upset

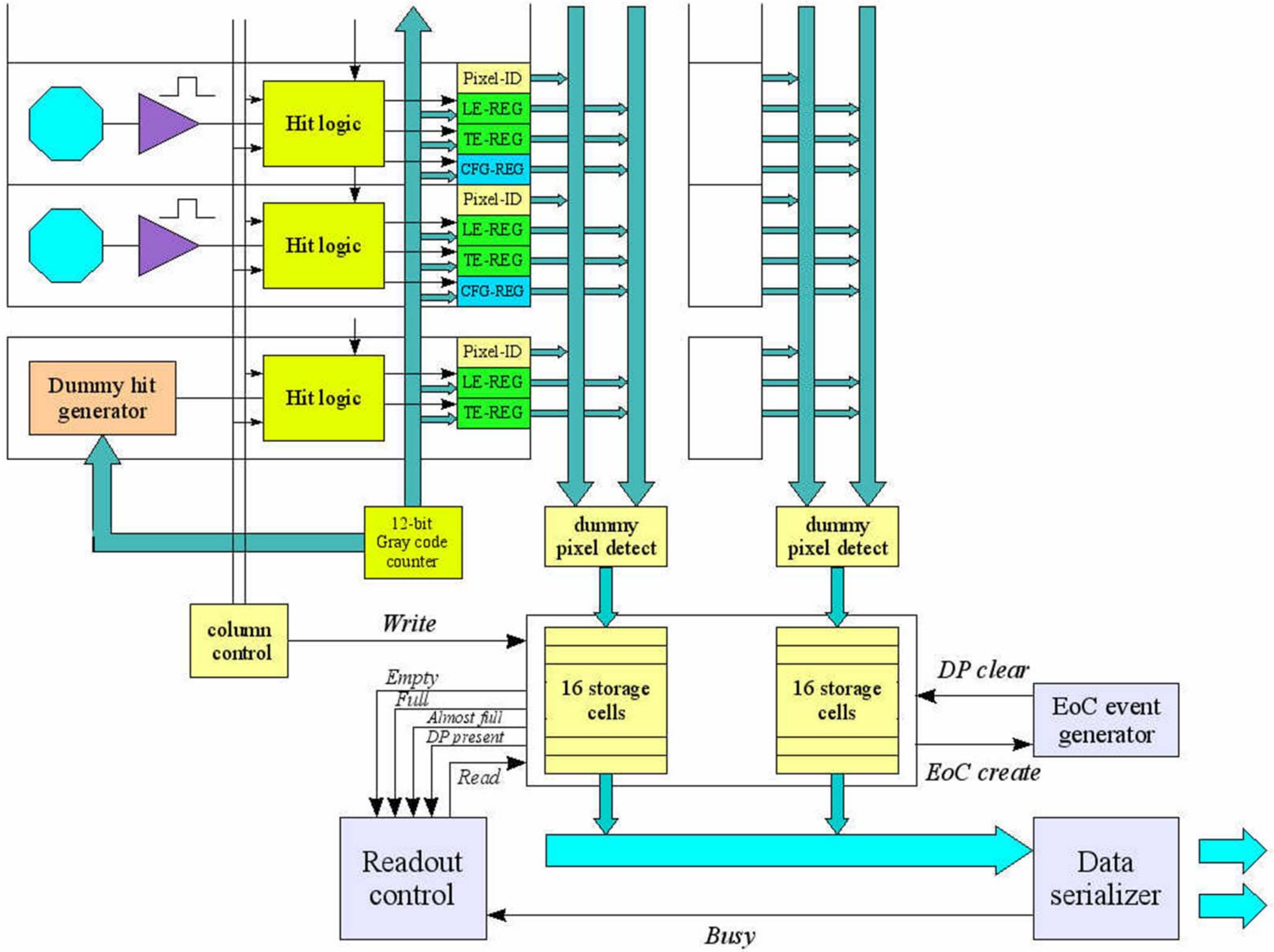


Material budget breakdown

	Pixel disk		Pixel stave	
	Thickness	% X/Xo	Thickness	% X/Xo
ASIC	150 mm	0,16	150 mm	0,16
Sensor	100 mm	0,11	100 mm	0,11
Bus (polymide/Al)	300 mm	0,27	300 mm	0,27
Carbon foam layer	4 mm	0,42		
Carbon foam layer			2 mm	0,21
Carbon fiber support			200 mm	0,1

+ cooling pipe

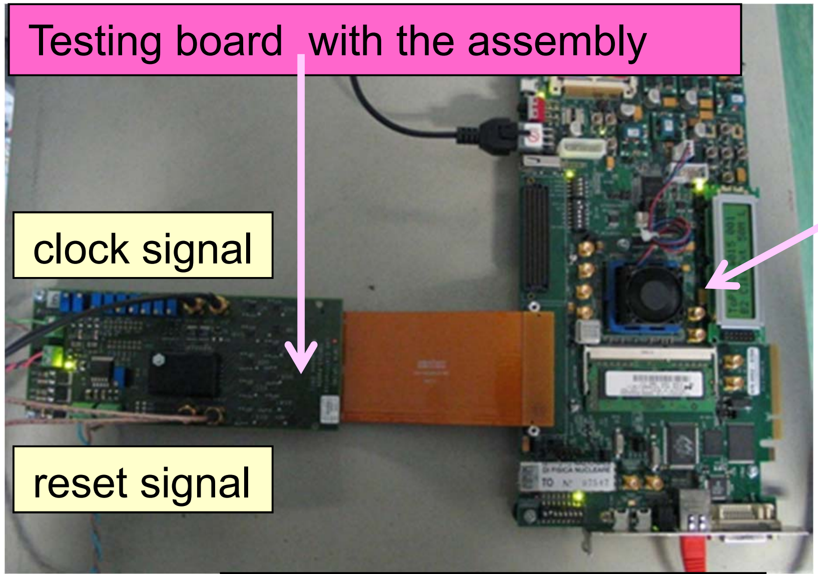
Column readout architecture



Acquisition setup

Testing board with the assembly

Xilinx Evaluation Board equipped with a Virtex 6 FPGA



clock signal

reset signal

Network connection to PC

LabVIEW Control