The ATLAS Hybrid Silicon Pixel Detector

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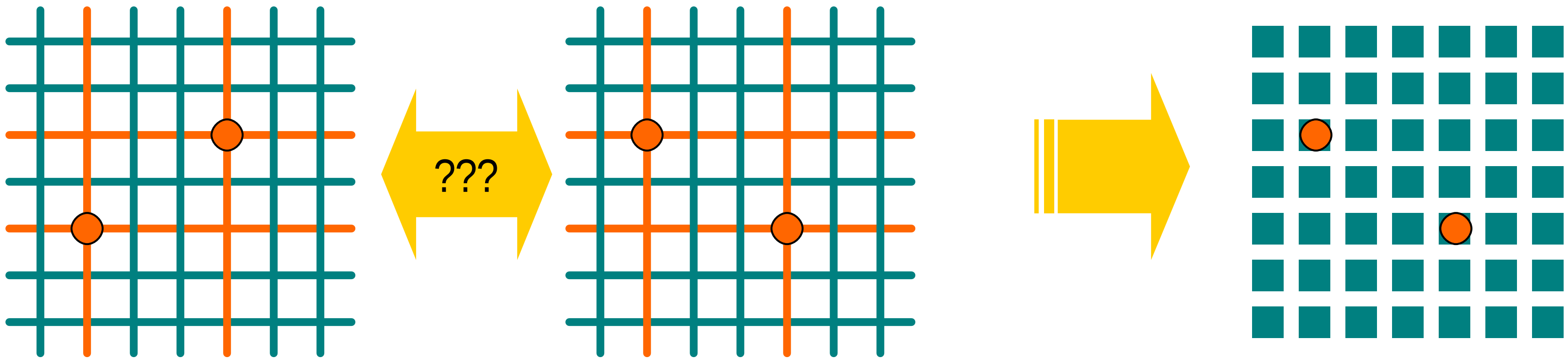
The ATLAS Pixel Detektor

- Why pixels - Introduction
- The pixel detector
  - Modules, mechanics etc.
  - The silicon sensor
  - The front end electronics
- Some results
- Status of the project

Why Pixels ?

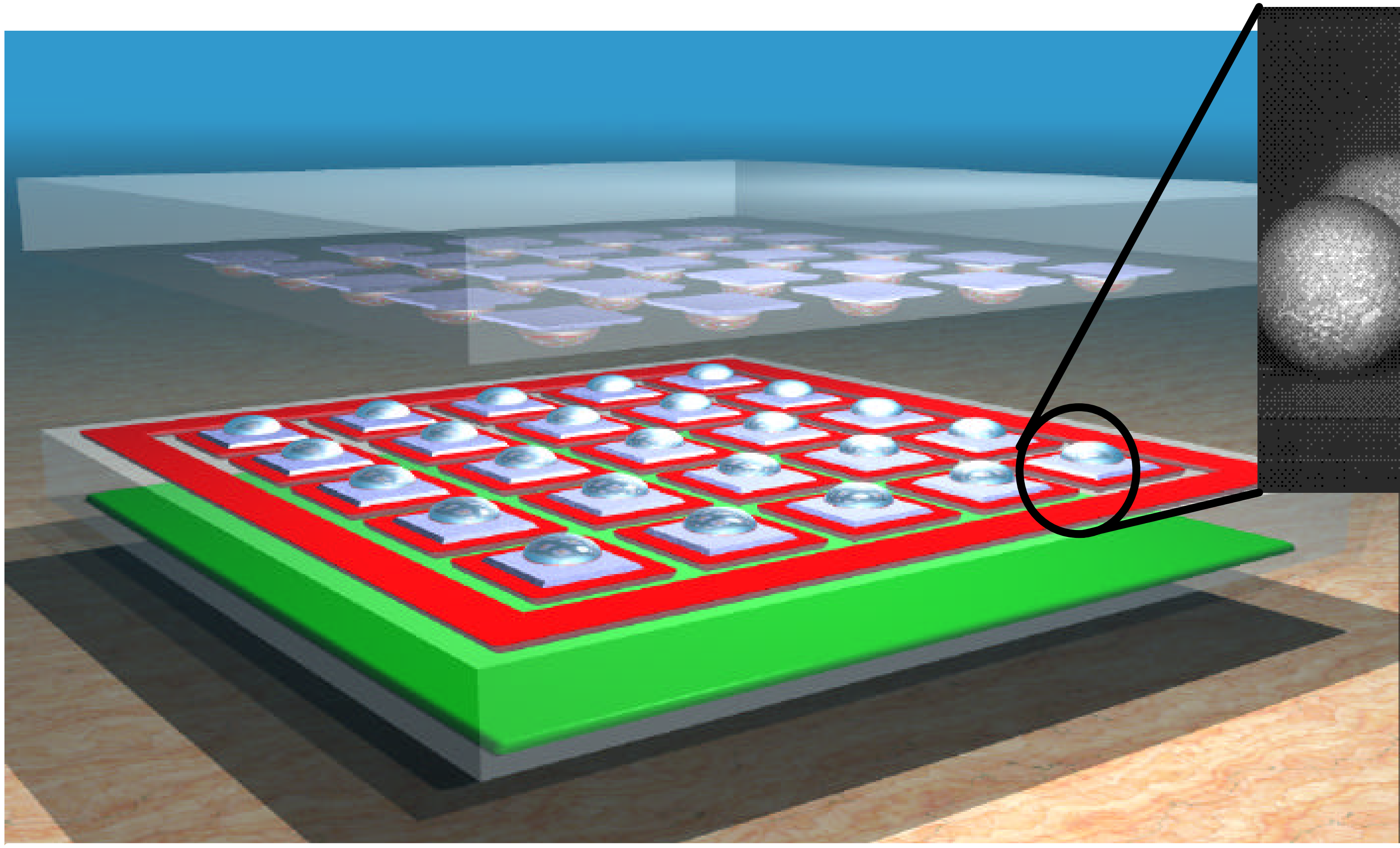
- Avoid ambiguities (‚ghost hits‘) at high multiplicities Þ need true 2D detector !

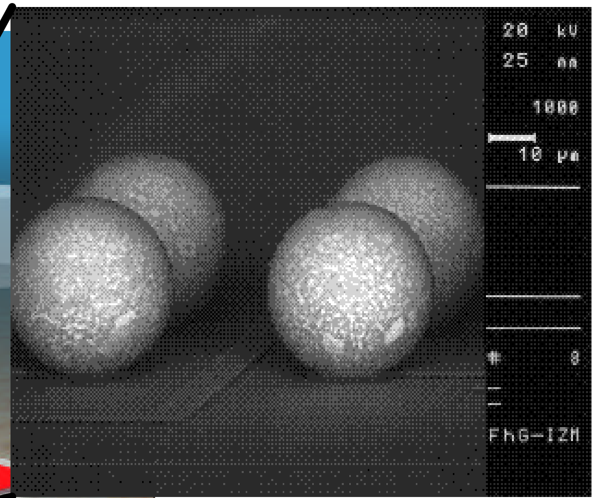


- Survive high radiation level Þ need very low noise

- Note: Strip detectors have better resolution & shorter radiation length!

Hybrid Pixel detectors





Bump pitch: 50µm
diameter: 20µm
(IZM, Berlin)

- Every pixel is connected to a separate amplifier on the readout chip
- Low input C ⇒ low noise ⇒ low threshold ⇒ can operate with thin detectors and small signals after irradiation ⇒ intrinsic radiation hardness

Requirements for the ATLAS pixel detector

▪ Pixel Size	50 x 400 μm^2	(as small as possible, limit is power)
▪ Typical Signal	1fC = 6000 electrons	(mip in 300µm silicon in pixel corner)
▪ Threshold	2000 electrons	(quite a bit smaller than signal)
▪ Noise	200 electrons	(quite a bit smaller than the threshold)
▪ Threshold dispersion	200 electrons	(not larger than the noise)
▪ Leakage current tolerance	100nA / pixel	(probably more than we need)
▪ Speed	25ns timing precision	(bunch crossing of LHC, 'time walk')
▪ Data storage	up to 160 clock cycles	(level 1 latency)
▪ Radiation Tolerance	50 Mrad, 10^{15} n/cm^2	(10 years operation)
▪ Power	50µW / pixel	(including periphery, ~ 10W / Module)
▪ Material	~ 1% X_0 per layer	
▪ Track efficiency	≥ 99 %	(including gaps between sensors)
▪ Many channels	10^8	(must have zero suppression)

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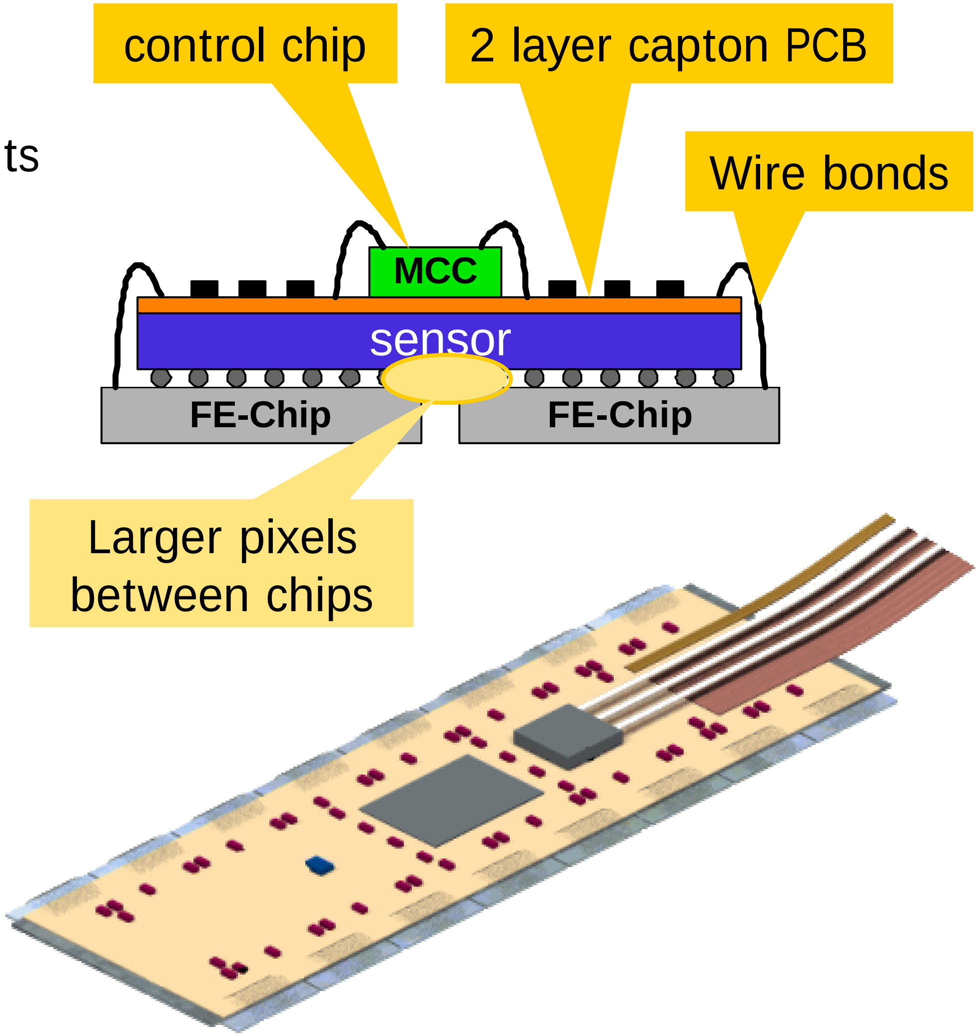
The ‚flex‘ Module

Flex capton solution:

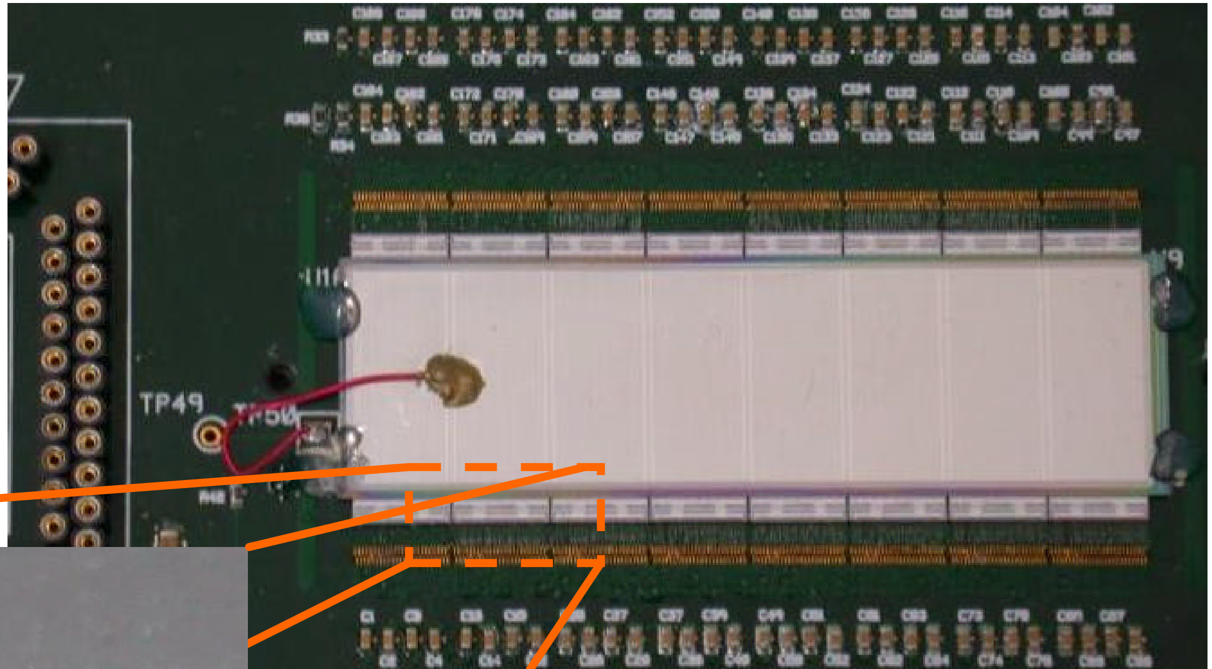
- Connections between FE-Chips, module control chip, other components and cable through a thin capton PCB
- Size = 16.4 × 60.8 mm^2
- 16 chips with ~ 50000 pixels total
- ~ 2000 modules needed



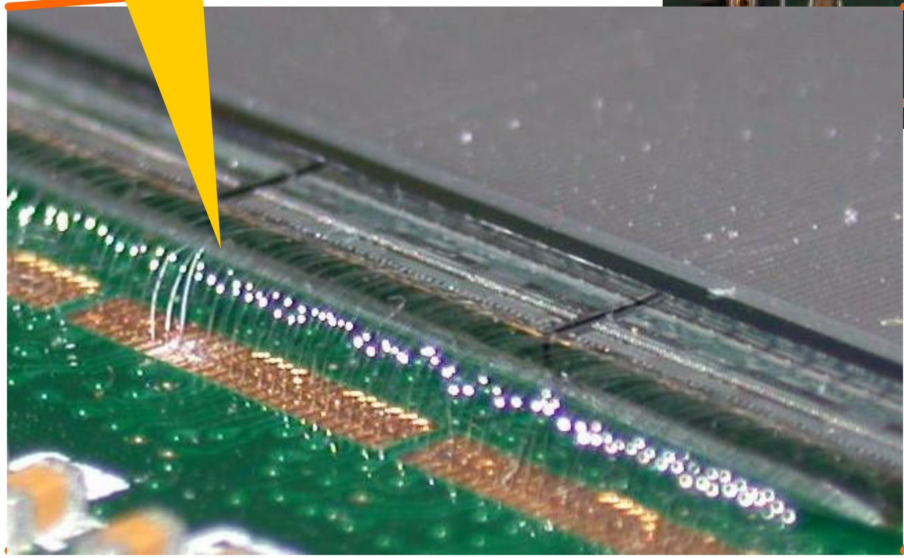
- Material:

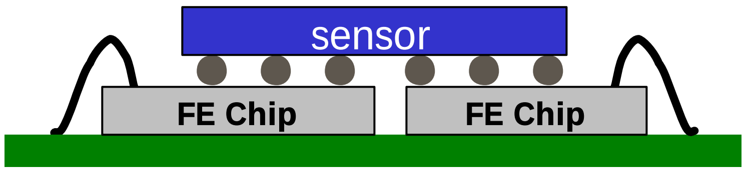
- silicon sensor	0.22 %
- chips thinned to 200 µm	0.14 %
- bumps, bonds, glue,…	0.10 %
- support, cooling, caps,…	0.90 %
Total:	1.4 – 1.8 %

1st generation: ‚bare' module on rigid support

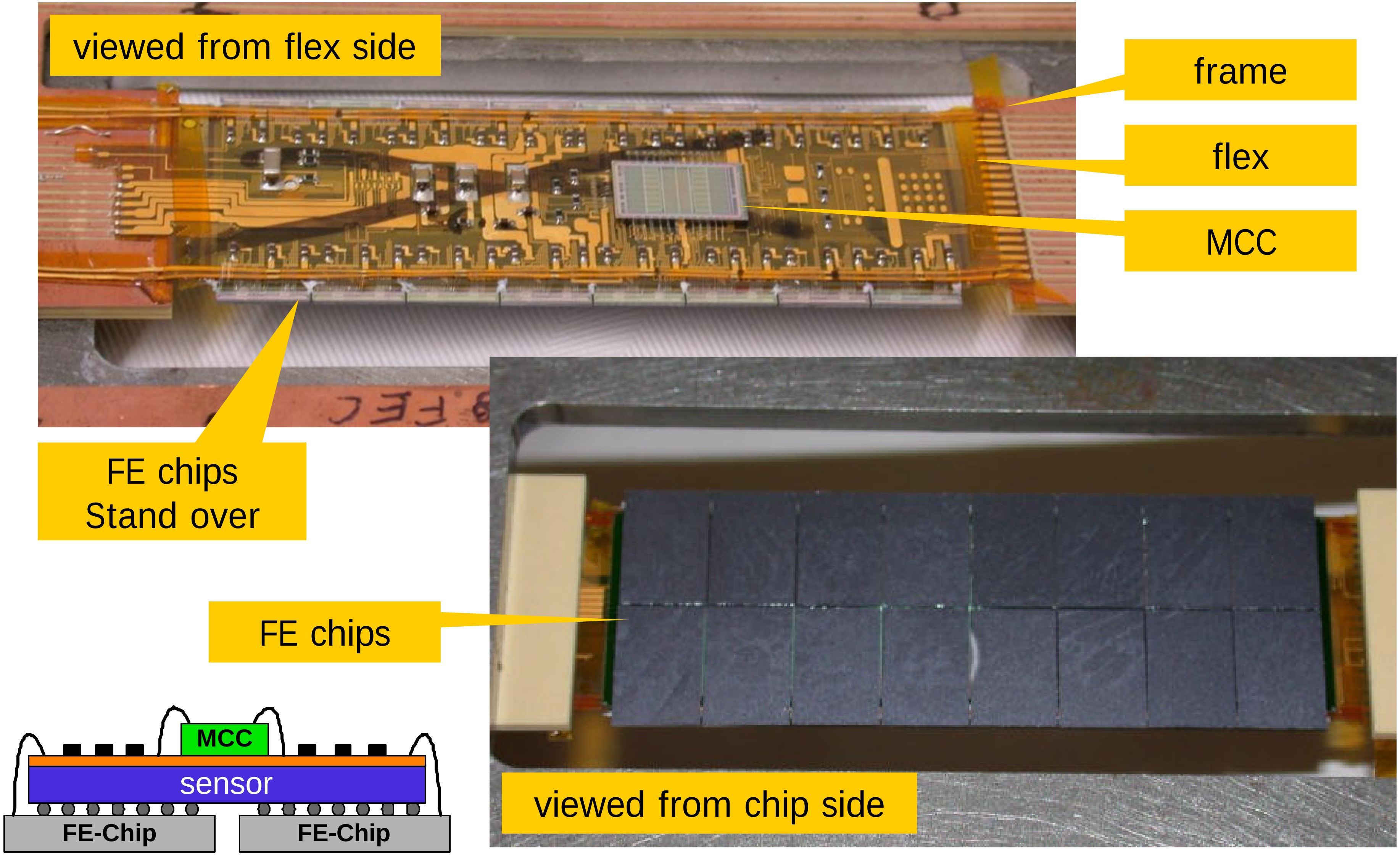


ALL wire bonds must be good!

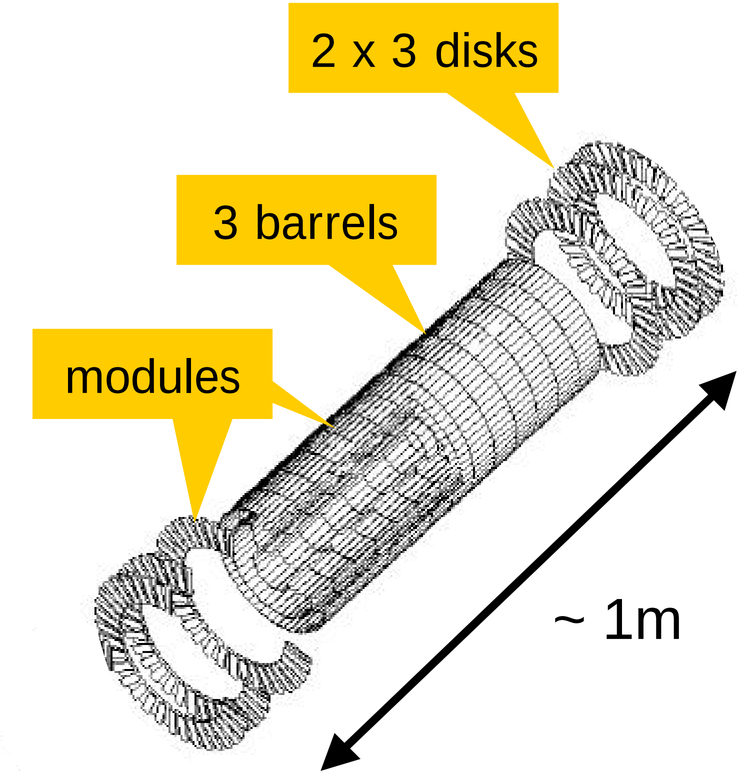


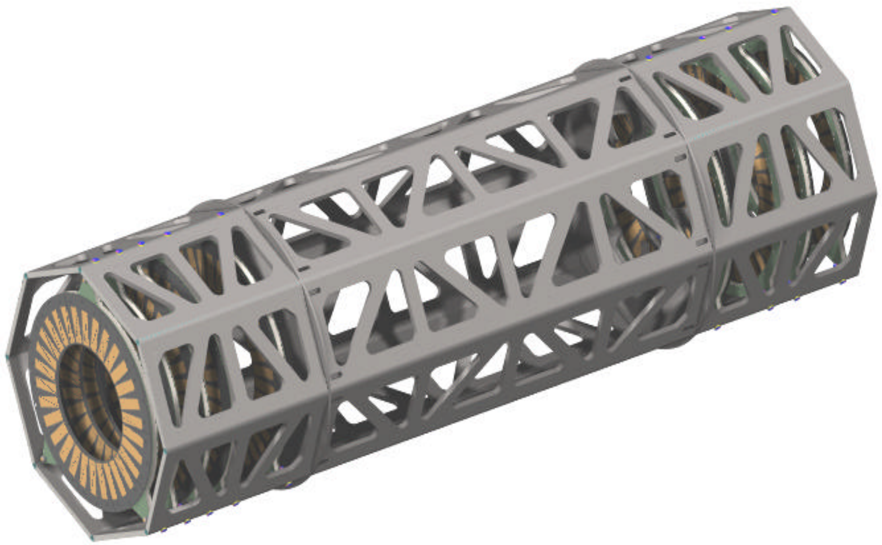


2nd generation: flex module in mounting frame



Overall layout





- Global support is a flat panel structure
- Made from carbon composite material (IVW, Kaiserslautern)
- Total weight is 4.4kg
- 3 pieces, center part consists of two half-shells to open

Cooling

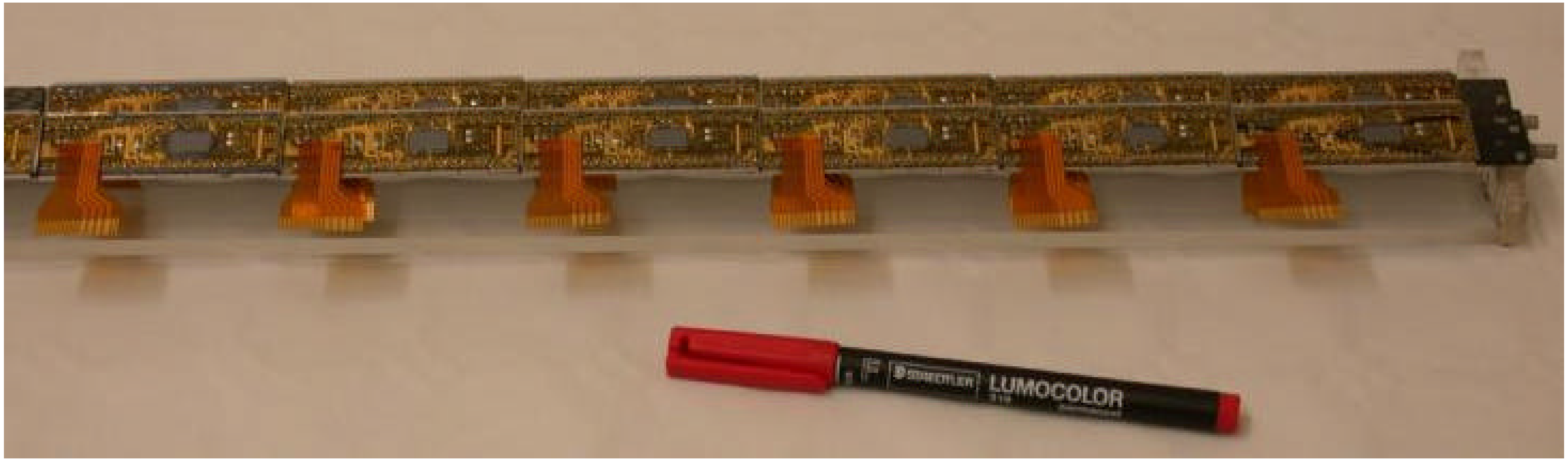
- Is very important
  - Contributes significantly to material budget
  - Limits the power / performance of electronics
  - Detectors must stay below $-6^{o}C$ to limit damage from irradiation (see later)

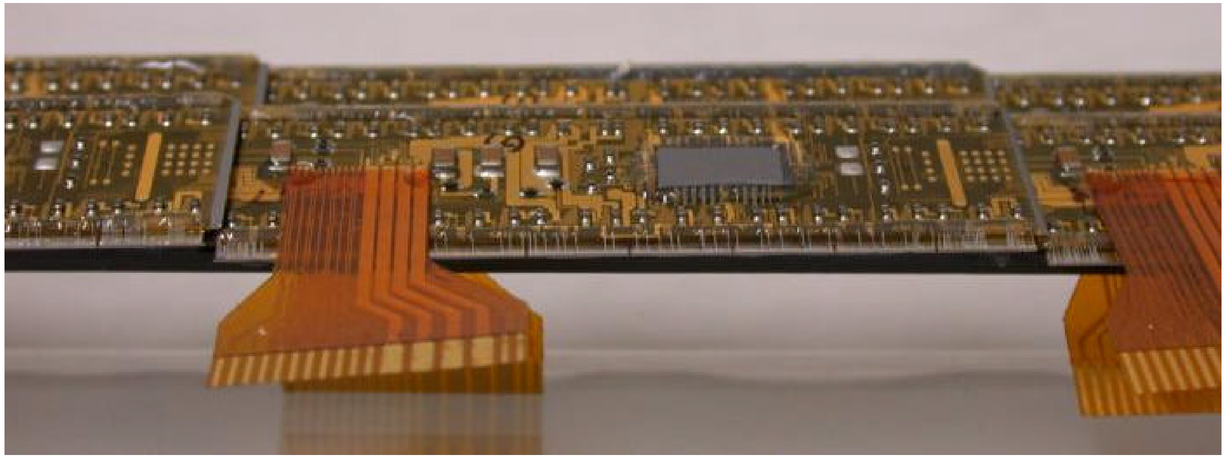
- ATLAS uses evaporative cooling:
  - Cooling by evaporation of fluorinert liquid (C_4F_{10} or C_3F_8) @ $-20^{o}C$. Needs pumping.
  - Low mass (gas!)
  - small diameter tubes (only small pressure drops)
  - Very large cooling capacity
  - Aluminum tubes must withstand 6 atm if pumping stops and coolant develops its full vapor pressure.

- All components must cope with thermal cycling $25^{o}C \Leftrightarrow -20^{o}C$

Barrels and staves

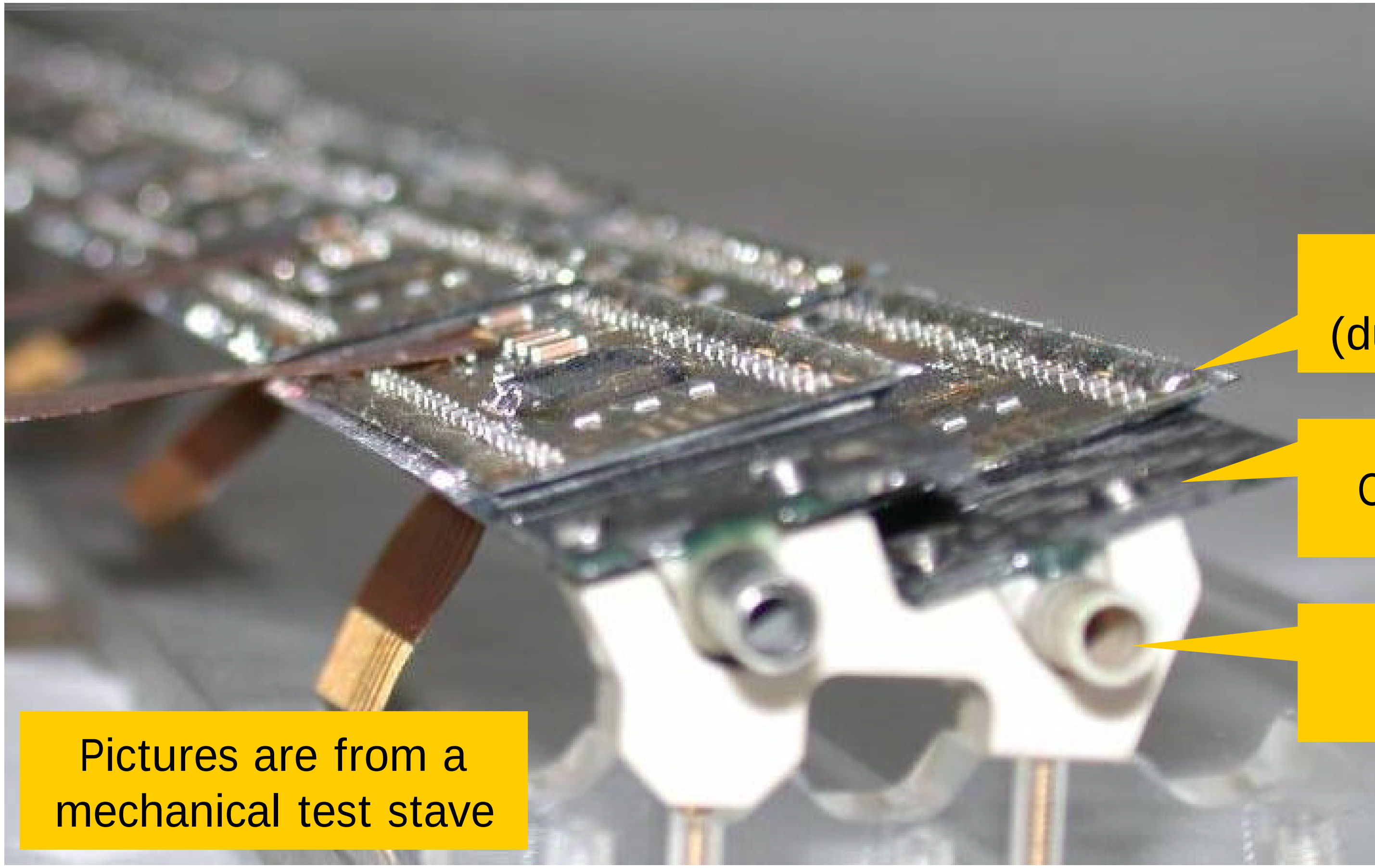
- Barrels are made from parallel staves
- One stave contains 13 modules which are shingled for overlap in z





Barrels and staves

- Stave is a carbon structure with an Al tube for cooling
- Staves are tilted for overlap in phi (+change sharing)
- Production mainly in Germany, Italy, France



Shingled (dummy) modules

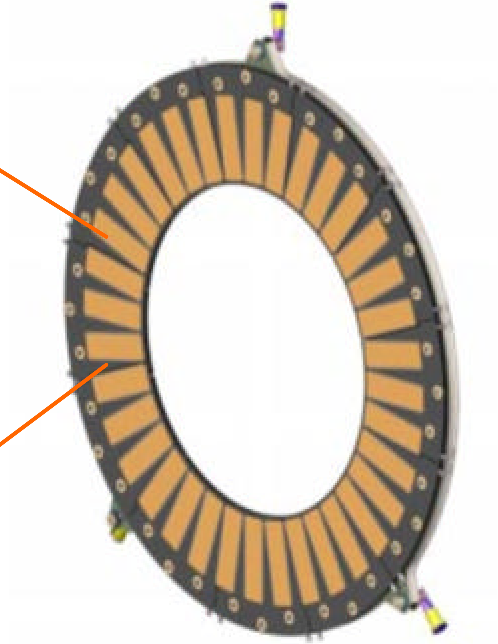
Carbon support

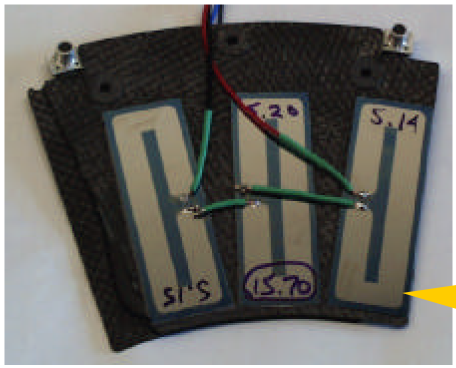
Al tube for coolant

Pictures are from a mechanical test stave

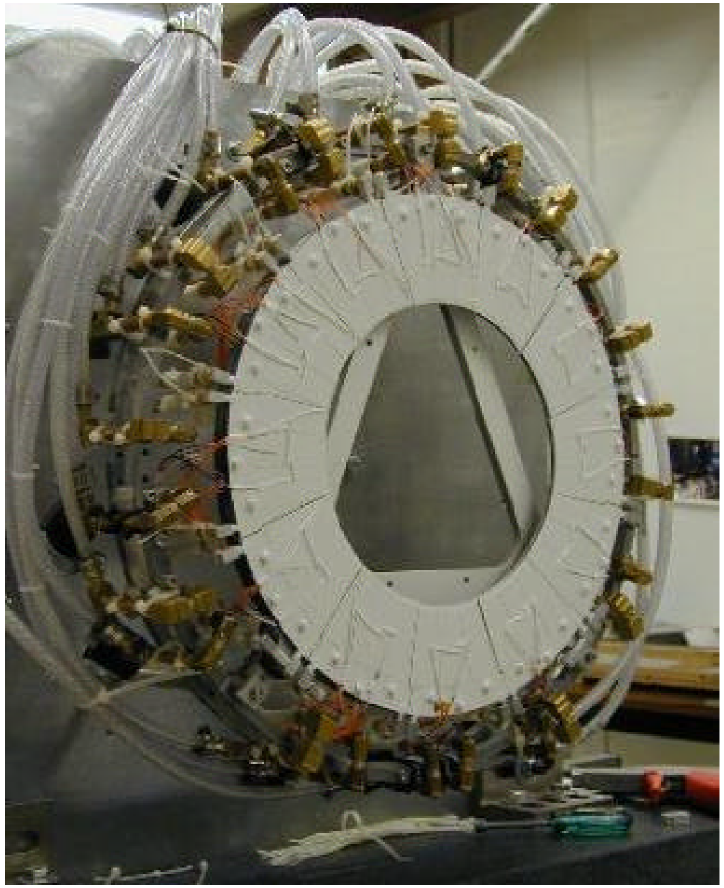
Disks and Sectors

- Disks are divided into sectors
- Coolant flows in tube between two C-C facings
- Modules are arranged on both sides for overlap
- Production in USA





Sector with 3 ‚modules'

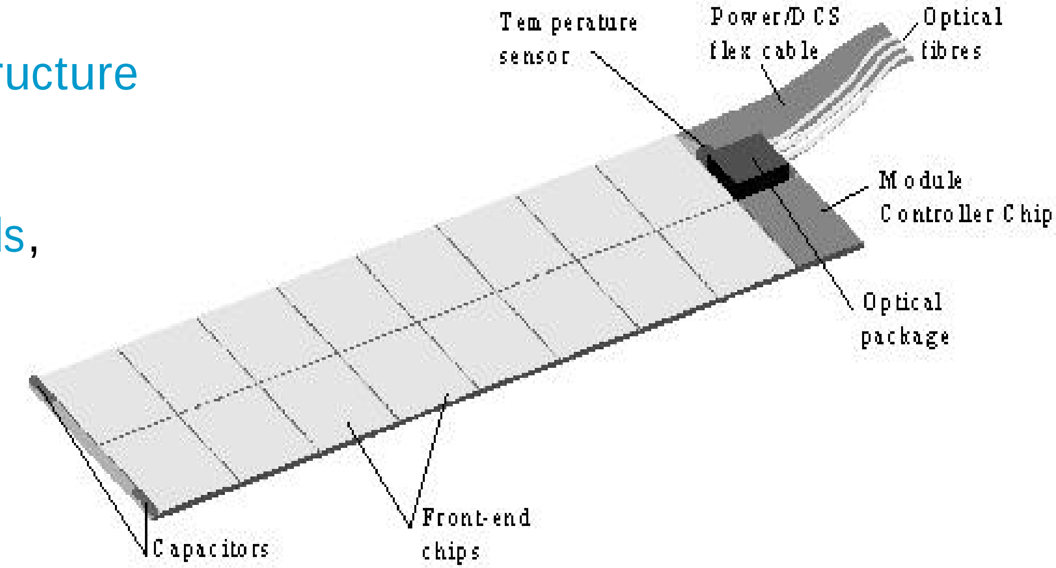


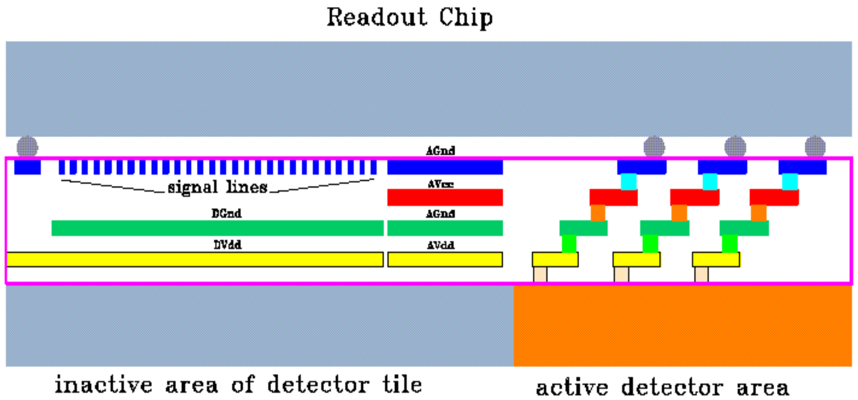
cooling test of full disk
(@ LBNL)

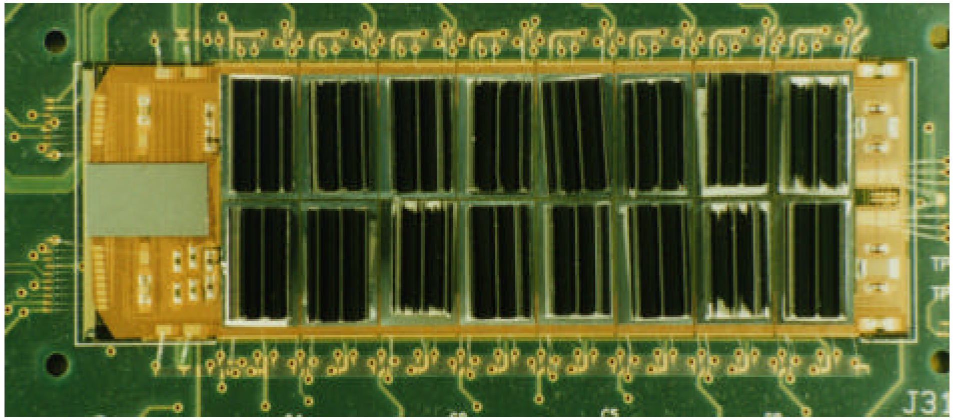
The MCMD module concept

MCMD module:

- Capton is replaced by multi-layer structure deposited onto the sensor
- Very compact module, no wire bonds, all pixels can have same size!
- Slightly more material (‚balcony‘)
- First working module had excellent performance

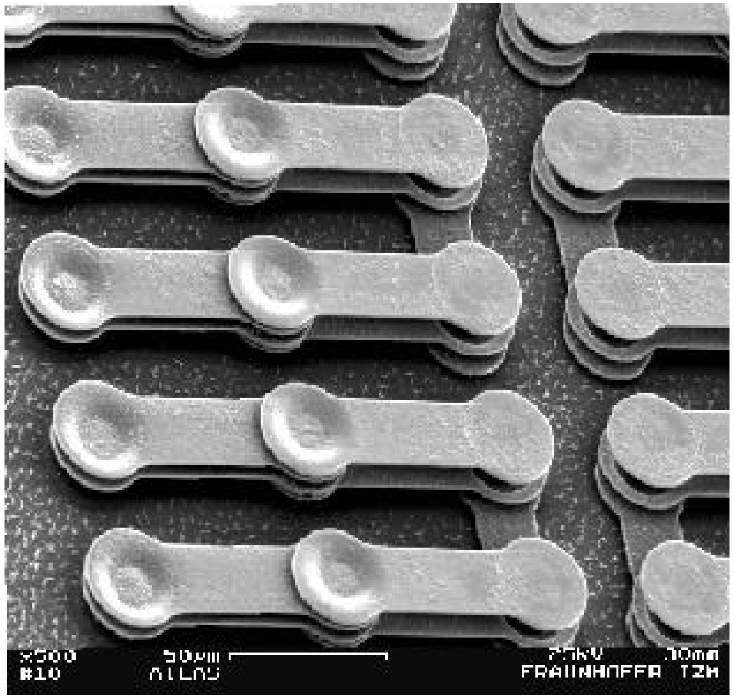


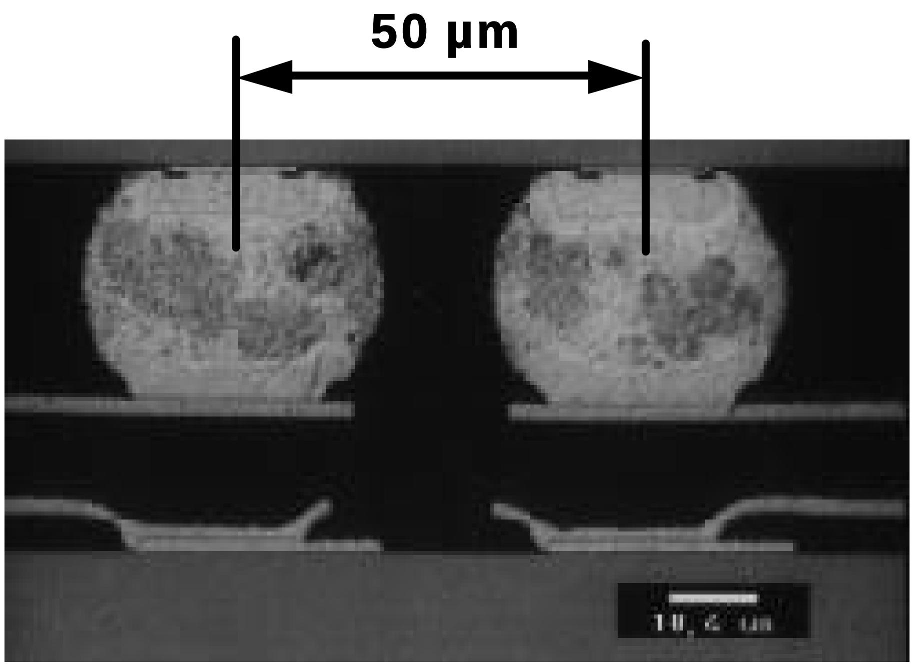


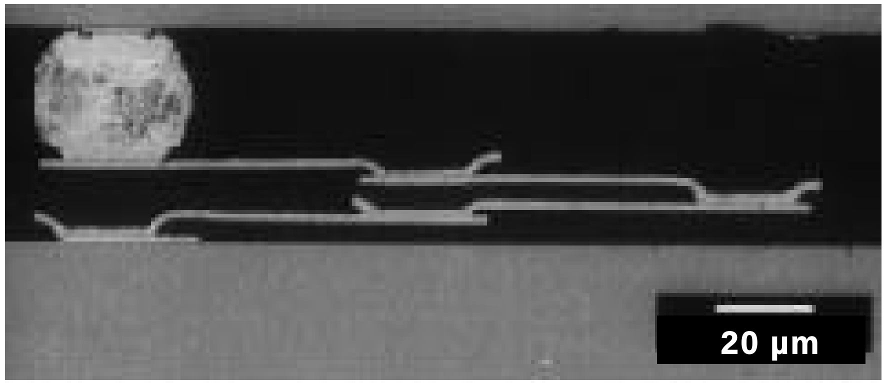


MCMD technology

- Production at Frauenhofer Institut IZM (Berlin), still yield problems
- Bumping with lead-tin bumps at IZM
- Very interesting concept for many future applications!







The ATLAS Pixel Detektor

Why pixels - Introduction

The pixel detector

- Modules, mechanics etc.
- The sensor
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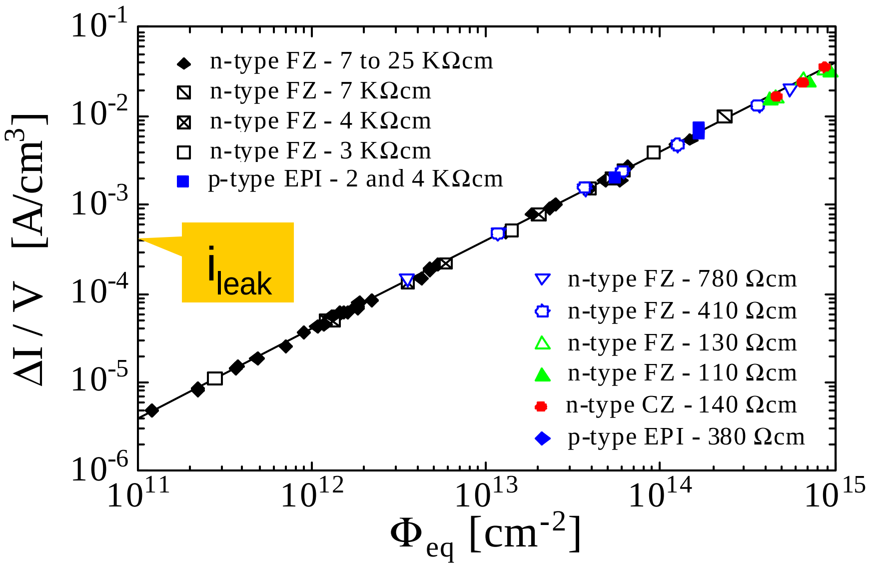
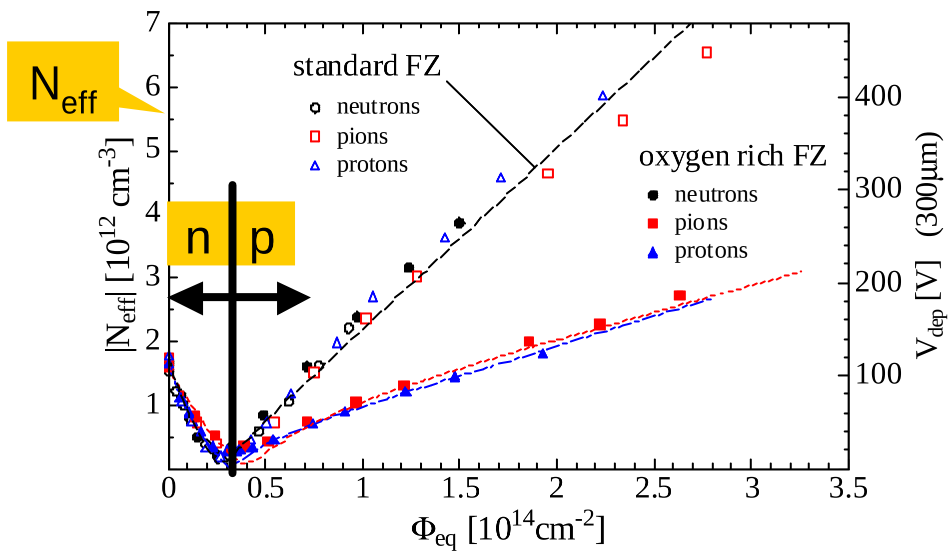
Some results

Status of the project

Radiation damage of silicon sensors

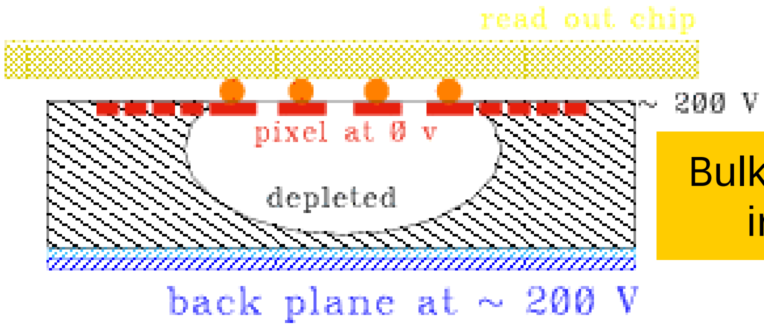
- Irradiation of silicon leads to bulk damage and oxide charges at the surface
- Bulk damage:
  - increased i_{leak} → increased noise
  - ‚reverse annealing' → keep sensor cold (- 6^0C)
  - Type inversion → n-side readout
  - Change in doping → increased depletion voltage (guard rings!) , partial depletion
- Oxide charges:
  - increased field strength → special designs



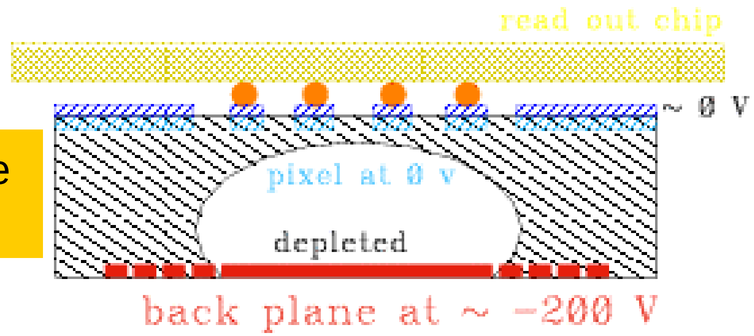


Problem of type inversion

p+ pixels on n- material

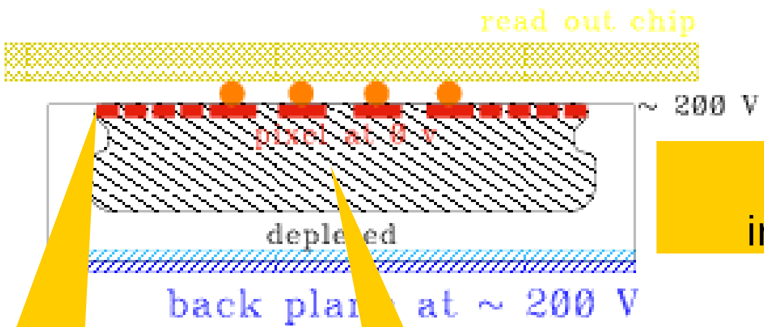


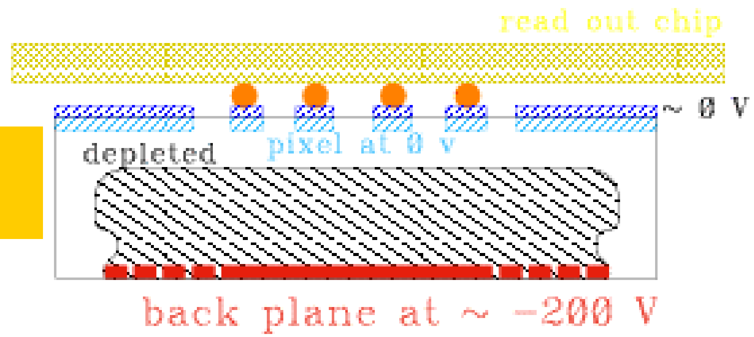
n+ pixels on n- material



Bulk is n- before irradiation

p- after irradiation





Voltage drop on Readout side

Need full depletion!

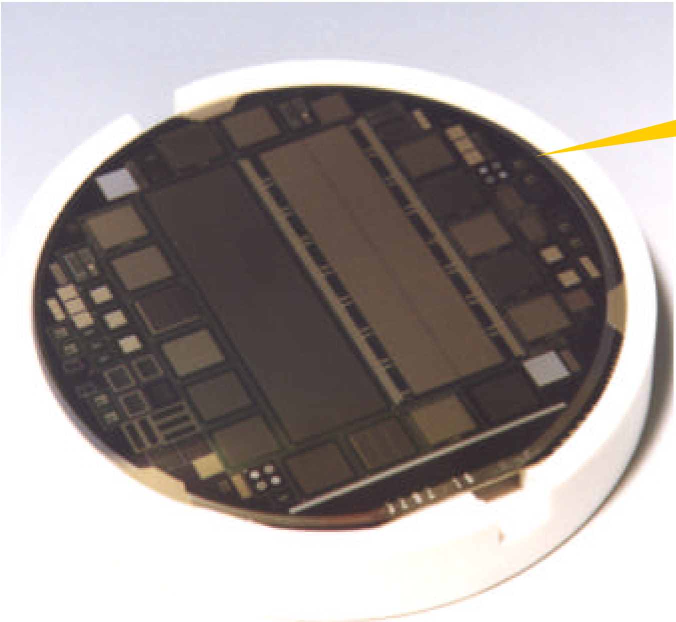
☹

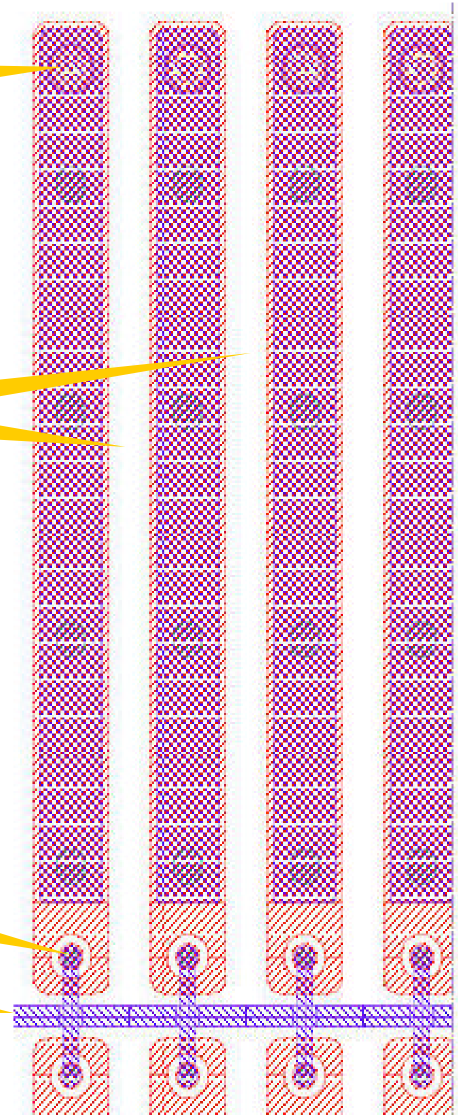
☺

Can be operated partially depleted

ATLAS pixel sensor production has started

- n+ pixels in n- sensor
- Multi guard ring structures hold up to 1000V
- Isolation of pixels with moderate dose p-spray has highest field strength BEFORE irradiation
- Punch through dot and bias grid for testing before bumping
- Use of oxygenated silicon



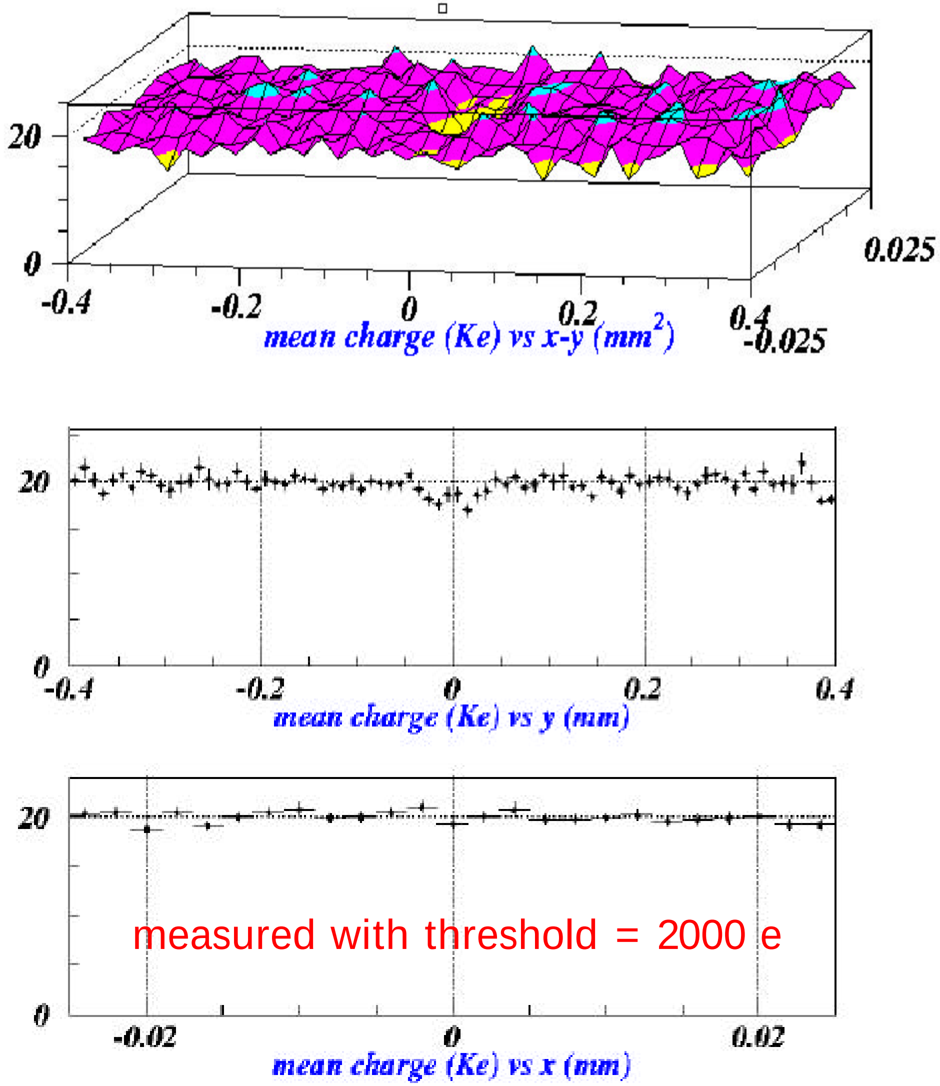


Performance of irradiated sensor

- Sensors are irradiated to full ATLAS fluence ($10^{15}\ n_{eq}/cm^2$)
- They are then bump bonded to rad-soft ATLAS Prototype FE-Chips
- Measurements are performed in test beam with a Si-Strip telescope as reference detector
- Pixel Chips give some information about collected charge.

RESULTS

- V_{bias} > 600V possible
- Homogenous charge collection also in pixel corners
- 98.4% track efficiency
- These sensors will survive 10 years of ATLAS operation



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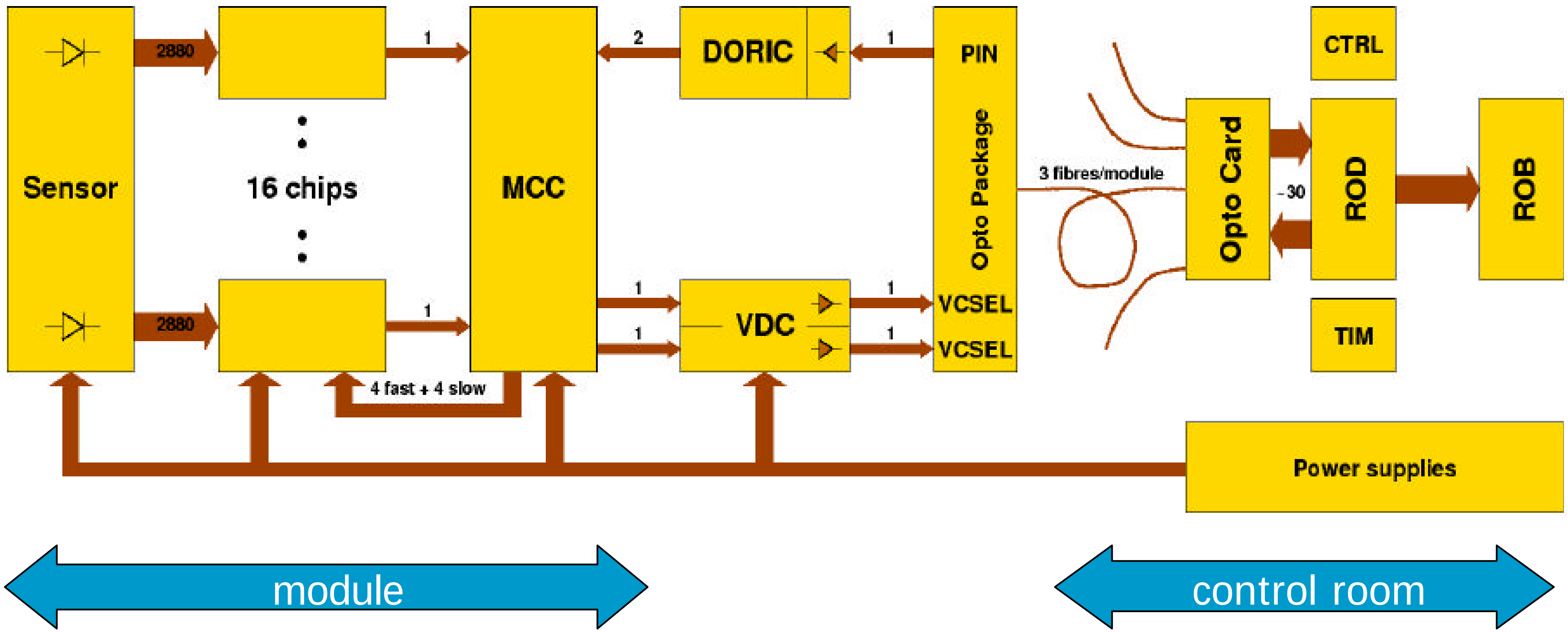
Electronic Components of the Pixel System



1	Sensor	
16	front end chips	(FE)
1	module controller chip	(MCC)
2	VCSEL driver chips	(VDC)
1	PIN diode receiver	(DORIC)

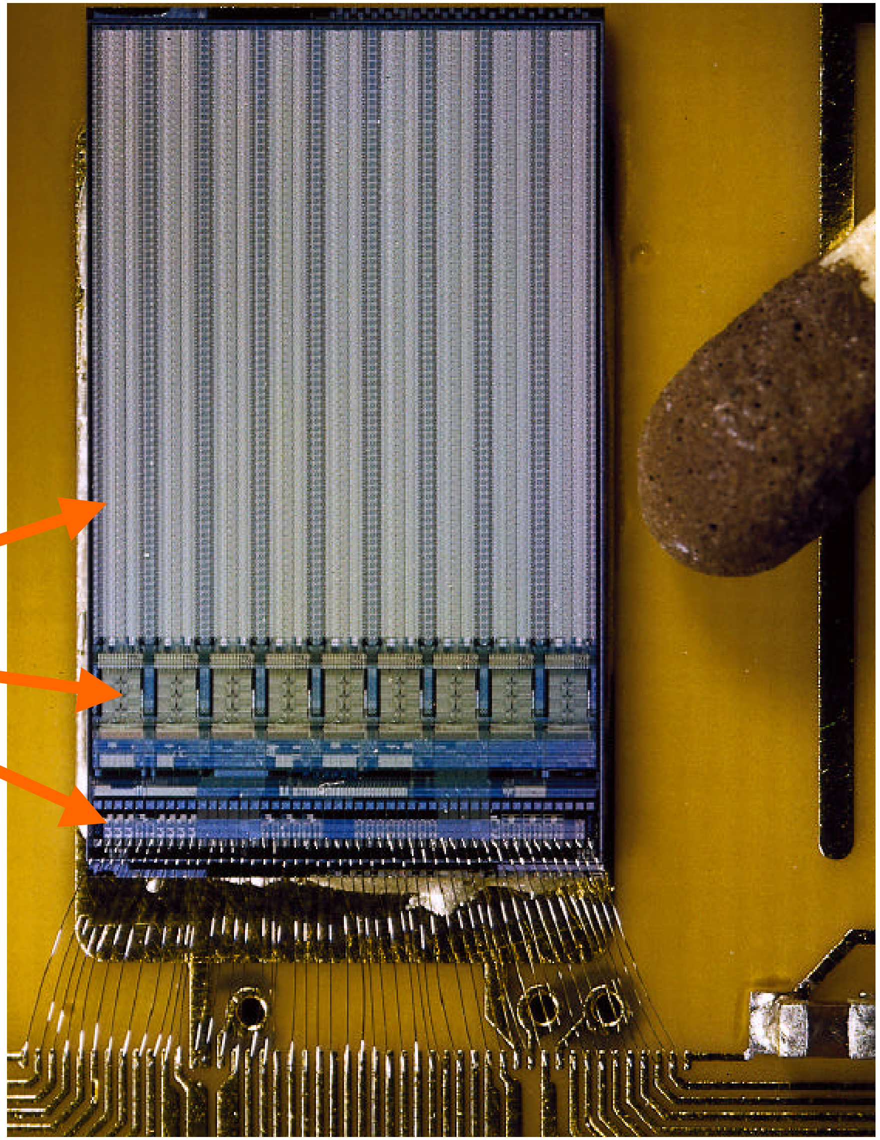
Optical receivers	
Readout Drivers	(ROD)
Readout Buffers	(ROB)
Timing Control	(TIM)
Slow Control, Supplies	

The Front End Chip

- Chip size: 7.4mm x 11mm
- Pixels: 18 x 160 = 2880
- Pixel size: 50µm x 400µm
- Technologies: 0.8µm CMOS (FEA,FEB)
  0.8µm BiCMOS (FED)
  0.25µm CMOS (FEI)

- Operates at 40 MHz
- Zero suppression in every pixel
- Data is buffered until trigger arrives
- Serial control and readout, LVDS IO

- Analog part with
  - 40 µW power dissipation / Pixel
  - ~200 e noise
  - Amplitude measured via pulse width

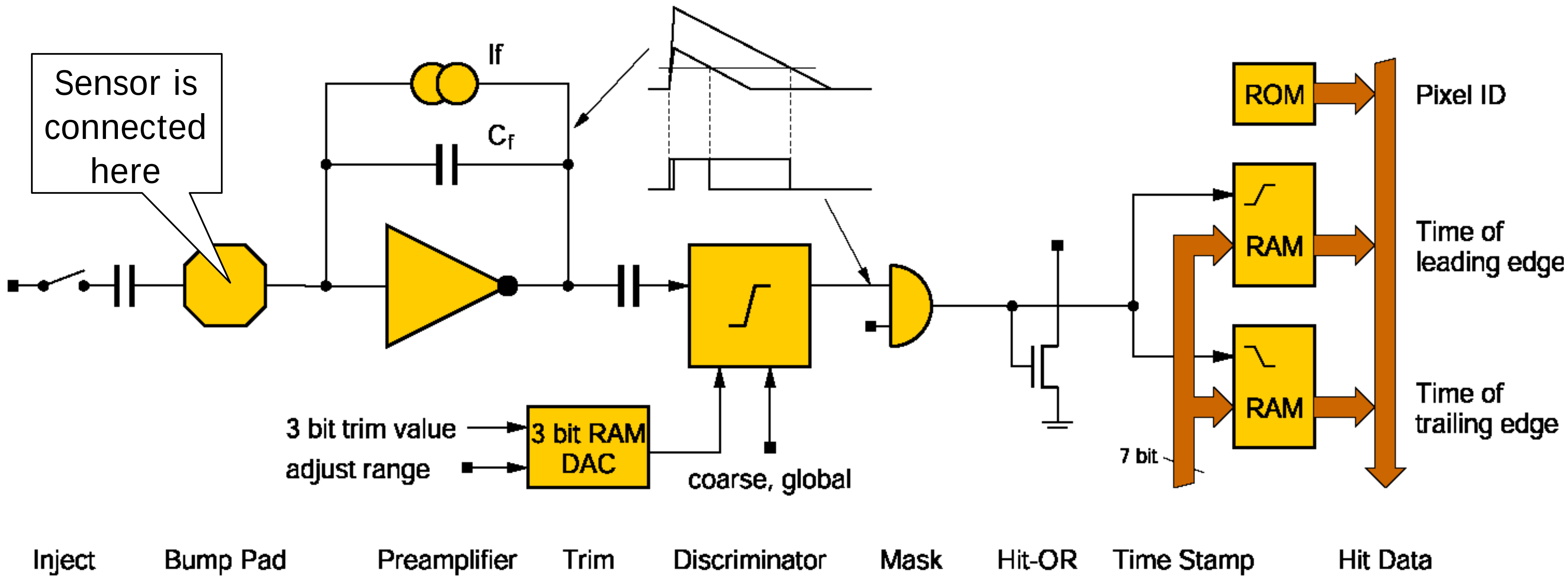


Pixel Analog Part

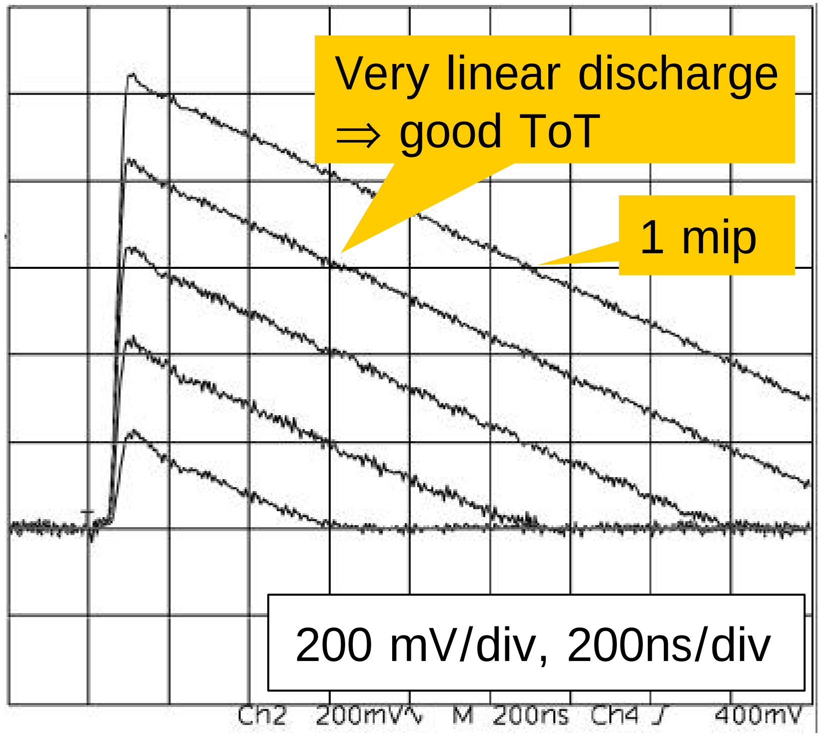
feedback uses constant current
- high stability for fast shaping
- tolerates > 100 nA leakage
- linear decay

Analog information
- measure width of hit
- works nicely due to linear discharge

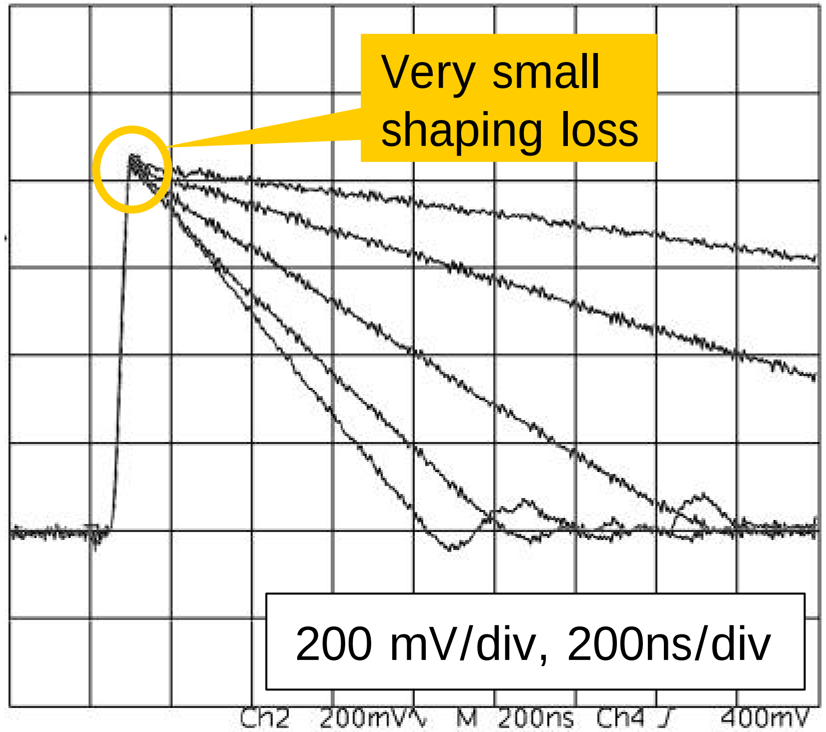
Individual adjustment of
- Threshold (5 bit in FEI)
- feedback current (FEI, 5 bit)
- ranges are adjustable



FED: Preamplifier Pulse Shapes



Different injected charges



Different feedback currents

(Measured on FED test chip with internal chopper, no sensor)

Data Readout

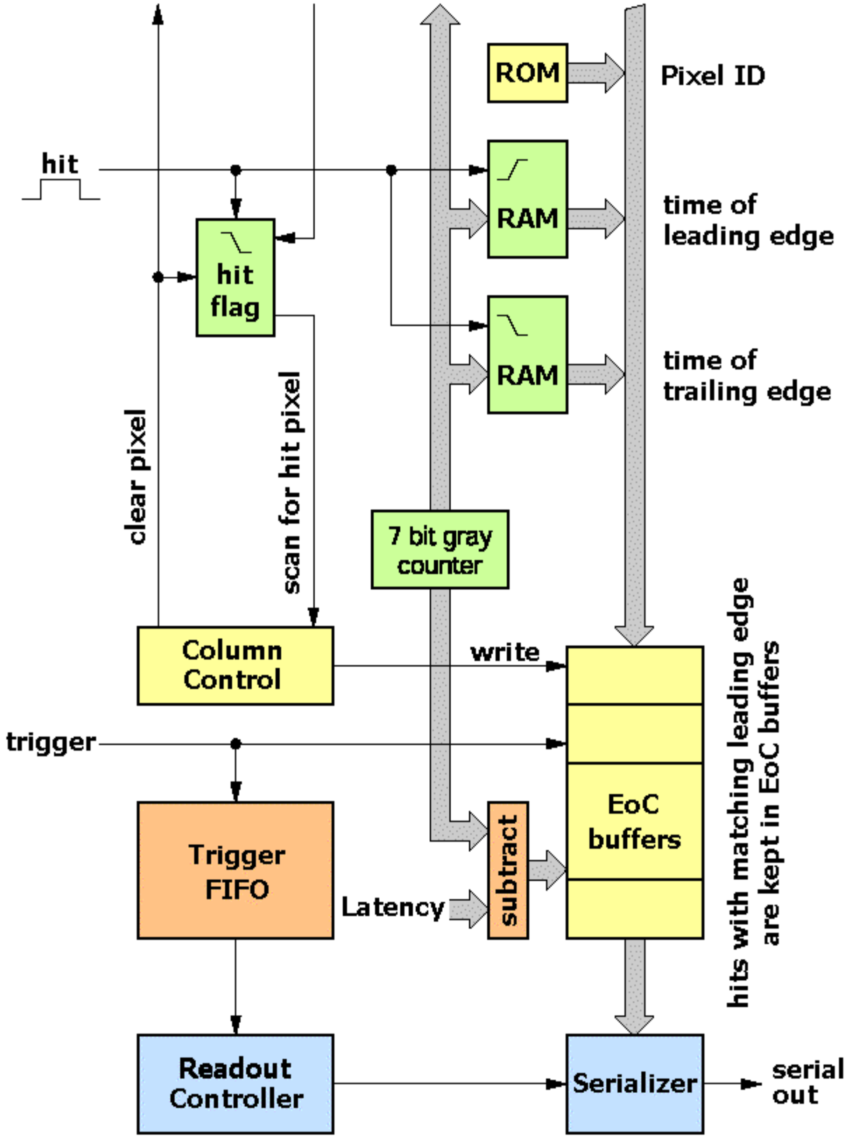
4 simultaneous tasks are running permanently:

- A time stamp (7bit Gray Code) is distributed to all pixels
- When a pixel is hit, the time of rising and trailing edges are stored in the pixel

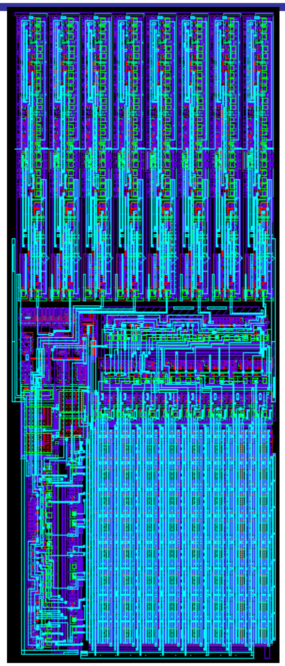
- The hit is flagged to the periphery with a fast asynchronous scan
- Time information and pixel number are written into a buffer pool (common to a column pair)
- The hit in the pixel is cleared

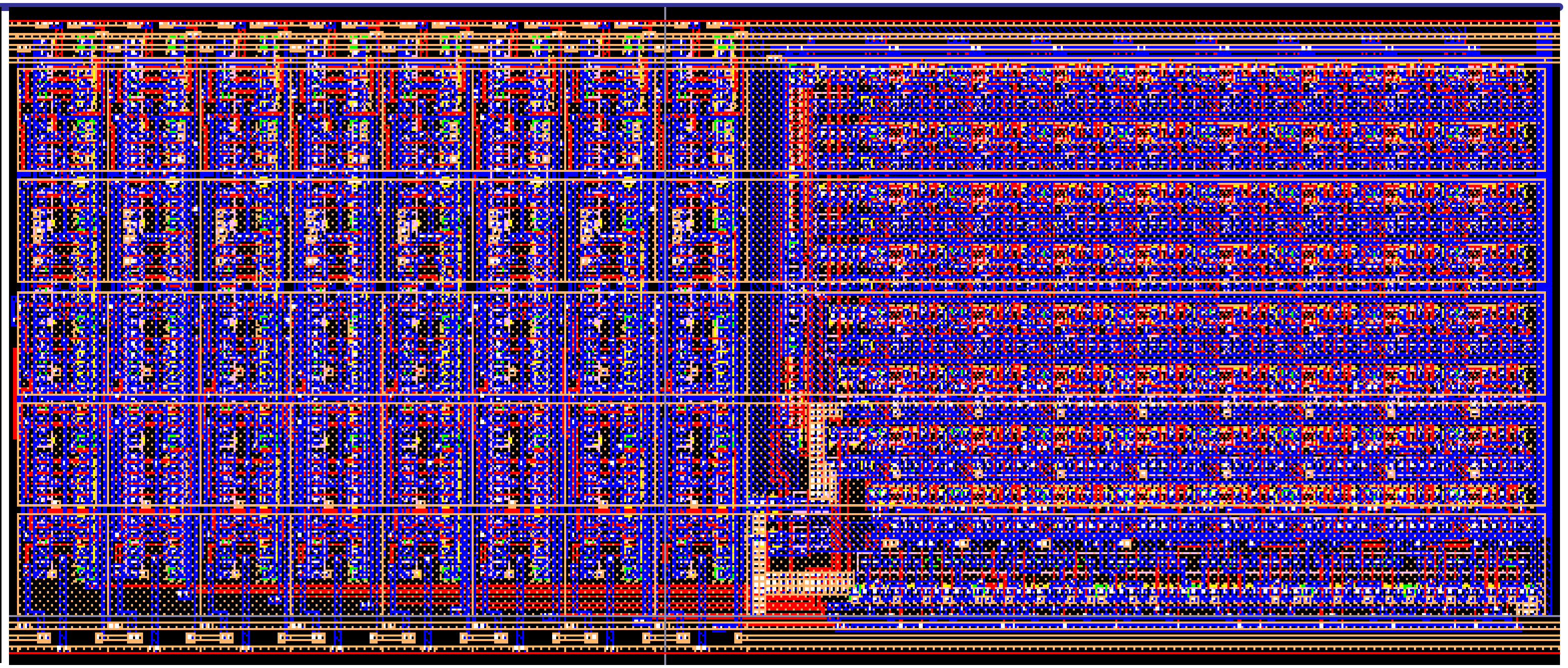
- If a trigger arrives, the time of the hit (leading edge data) is compared to the time for hits associated to this trigger. Valid hits are flagged, older hits are deleted.
- The trigger is queued in a FIFO

- All valid hits of a trigger are sent out serially. All triggers in the FIFO are processed.



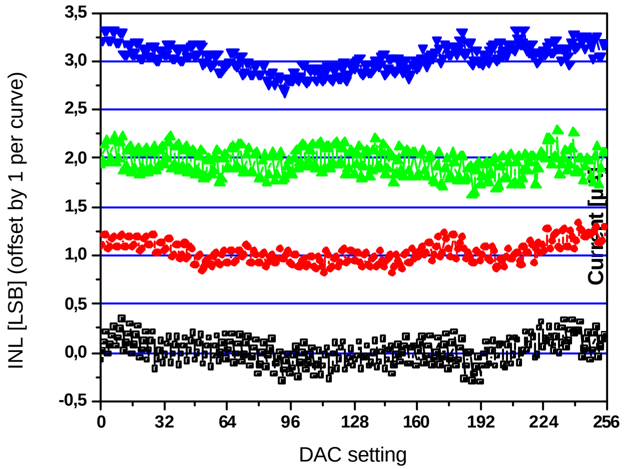
FEI design: from 0.8µm DMILL to rad hard 0.25µm

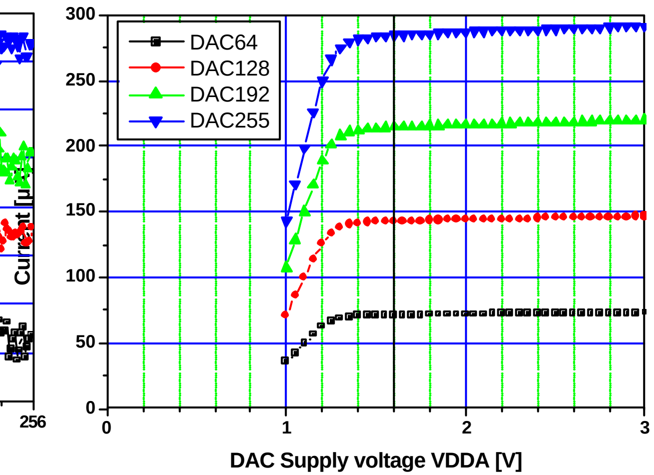




0.25µm
80x200 µm^2

DMILL
500x200 µm^2





Example: 8 bit DAC+Regs
full custom layout:
gain x 6 in area !

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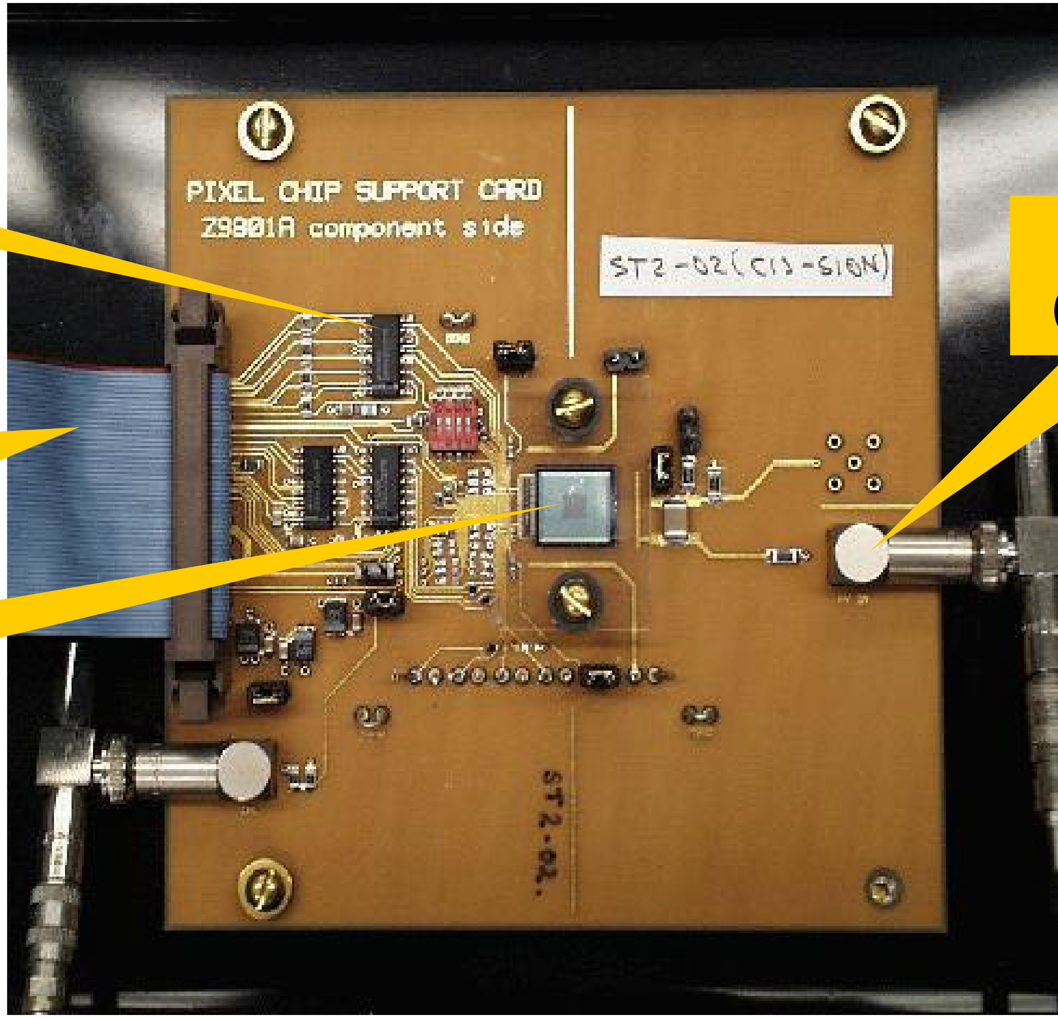
Results of single chip & module prototypes

LVDS IO

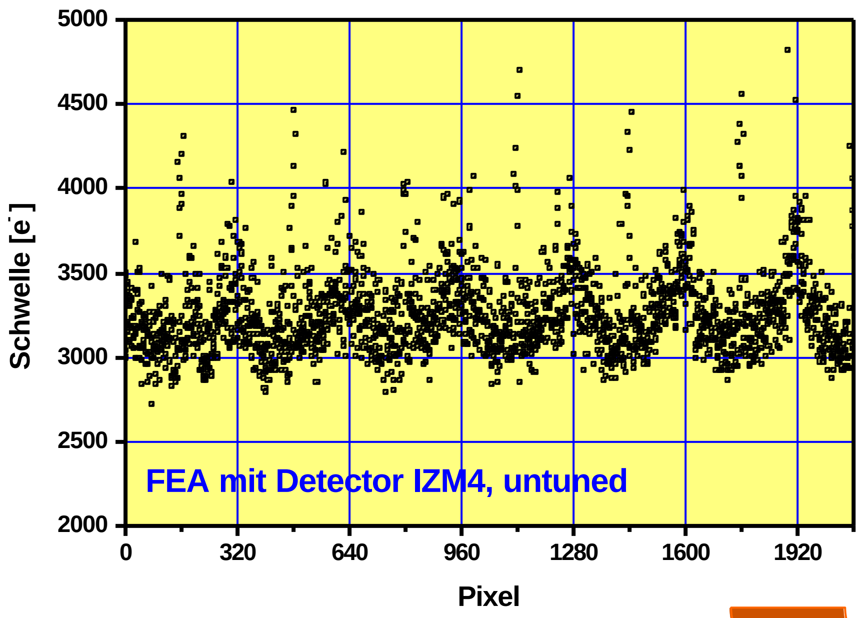
Cable to
power & DAQ

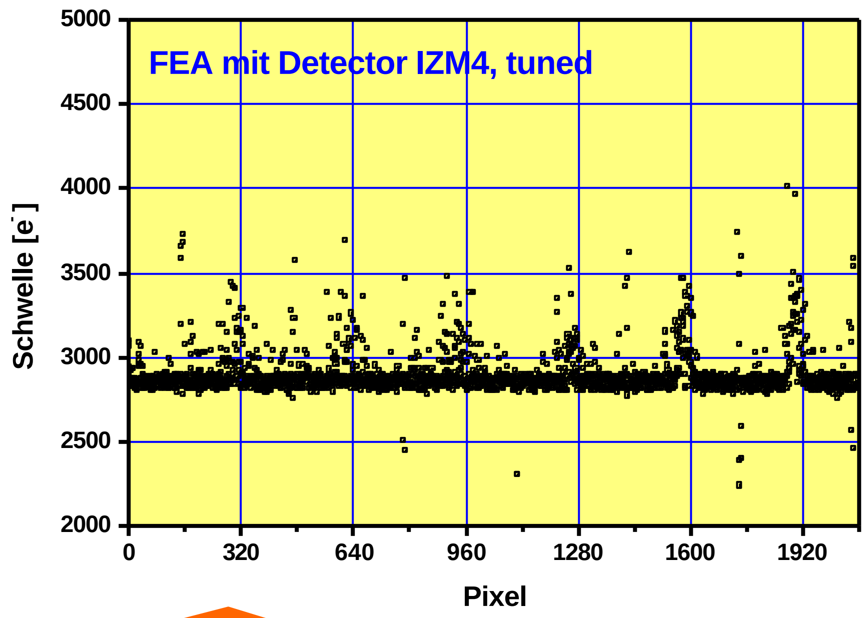
Single chip
with sensor



HV
(sensor bias)

Threshold adjustment on a single chip





Column structure, edge pixels!

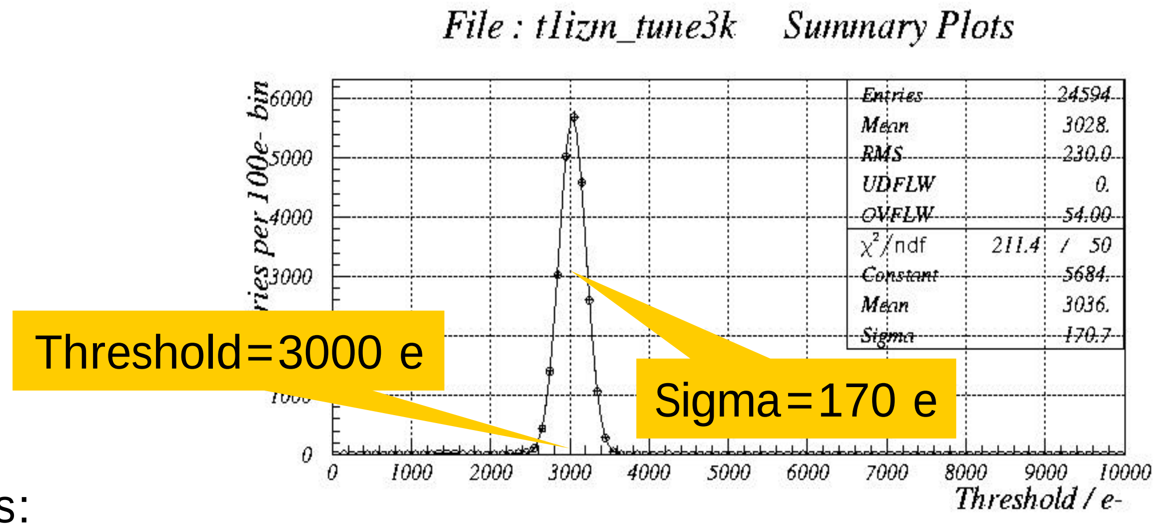
Still some bad thresholds !

Threshold trim

- Trim range can be selected to find best compromise between dynamic range and resolution
- Situation is much better in FEI with 5 trim bits !

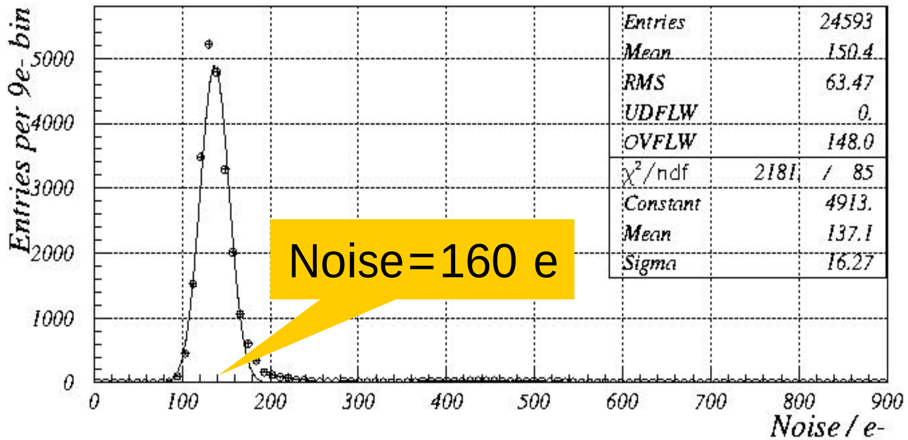
Module thresholds & noise

- Module with 16 chips, here FEB
- Threshold and Noise are comparable to single chips.

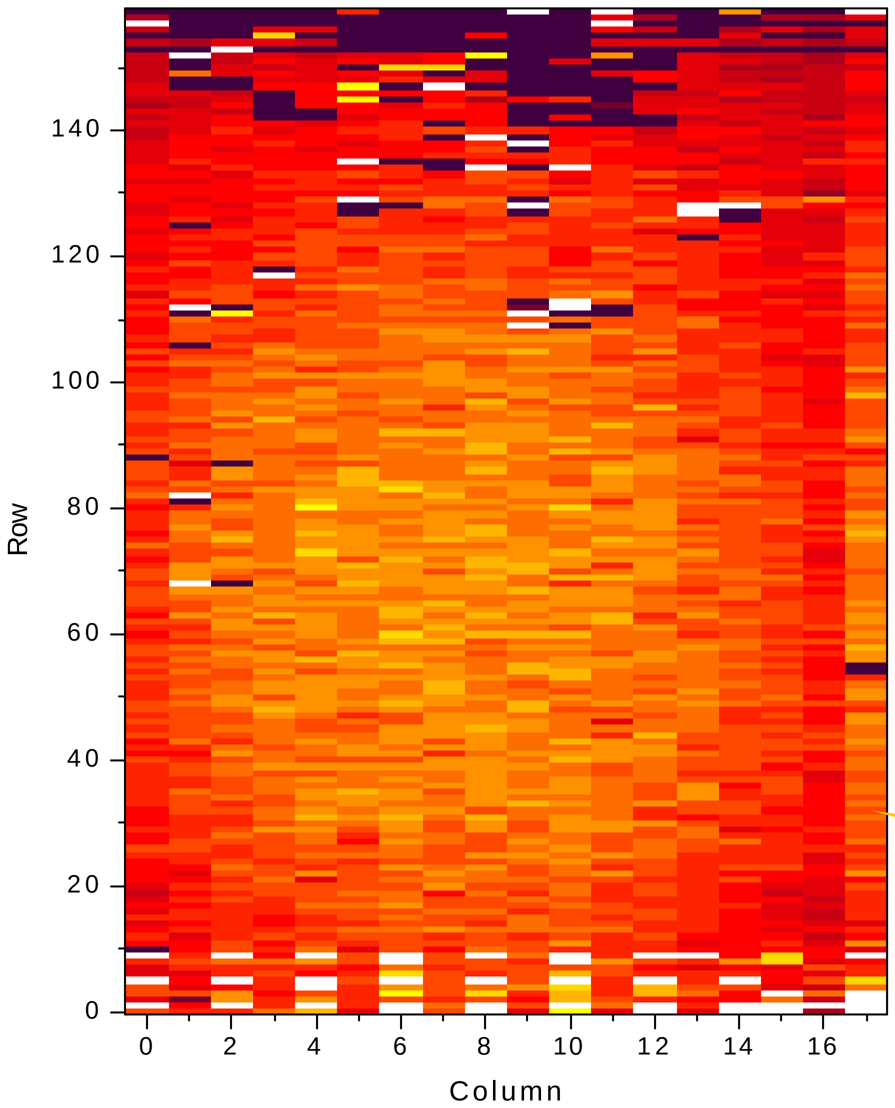


- Performance of several modules:

Module type	Front-end	Bump	Threshold [e]	Noise [e]
Bare	FEB	IZM	2000	140
Flex	FEB	IZM	2000	180
Bare	FEC	IZM	2500	140
Flex	FEB	IZM	3000	160
Flex	FEB	Alenia	3600	180



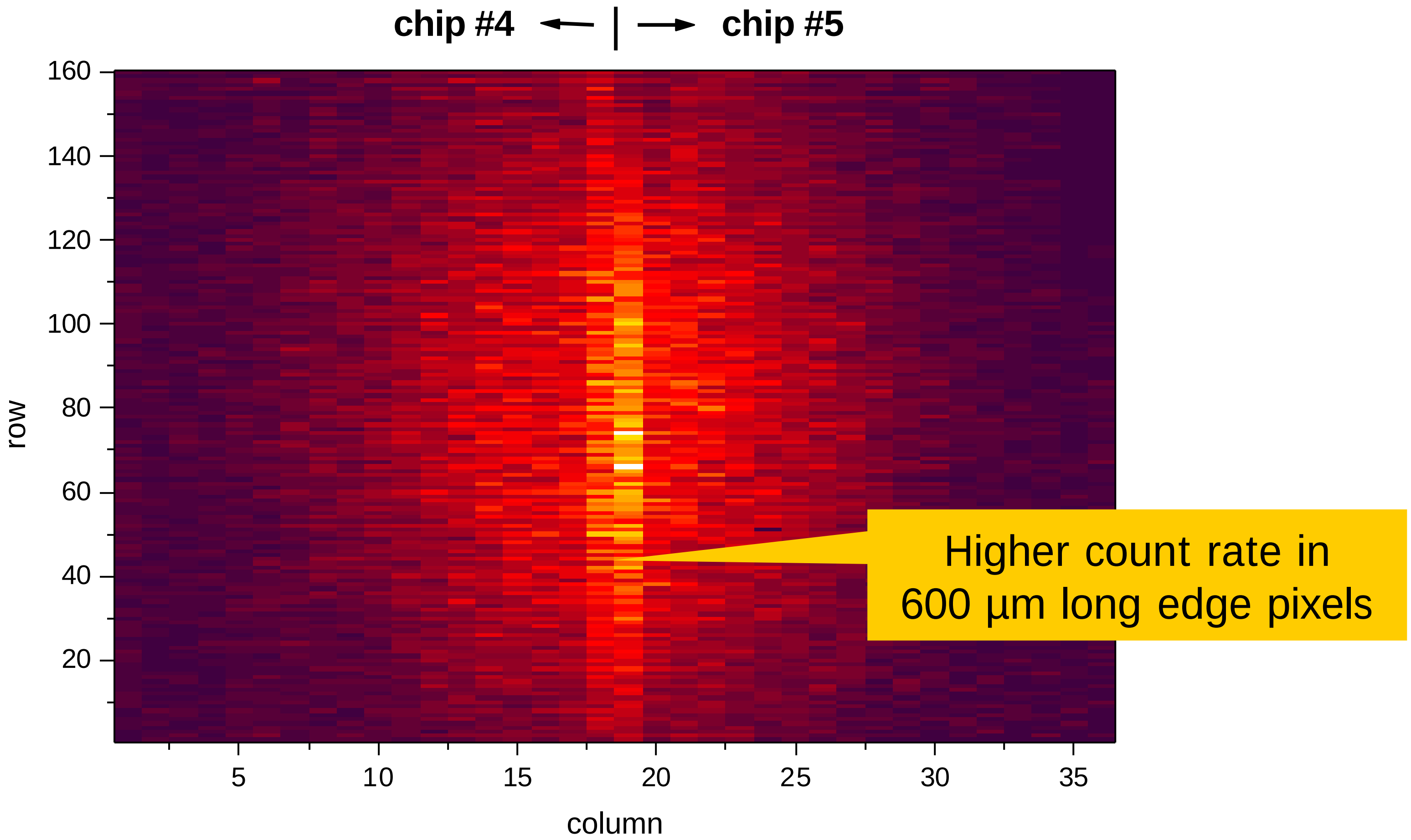
Source measurement with ^{55}Fe



- ^{55}Fe-source (6keV γ) deposits only 1700 e-h-pairs
- FE-C chip with thresholds tuned to ~1200 e^-
- Some bump problems at edge (one of the first assemblies)
- The chip can be operated at very low threshold

Edge sensors are longer (600 µm)
$\Rightarrow$ higher count rate

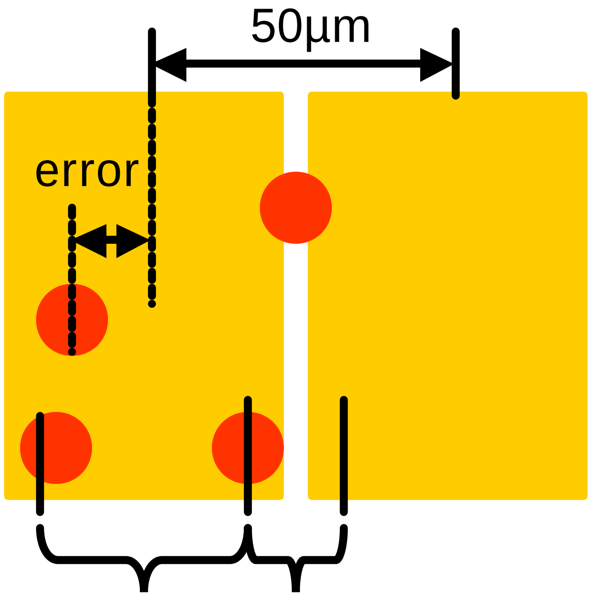
Source measurement on a module with ^{241}Am

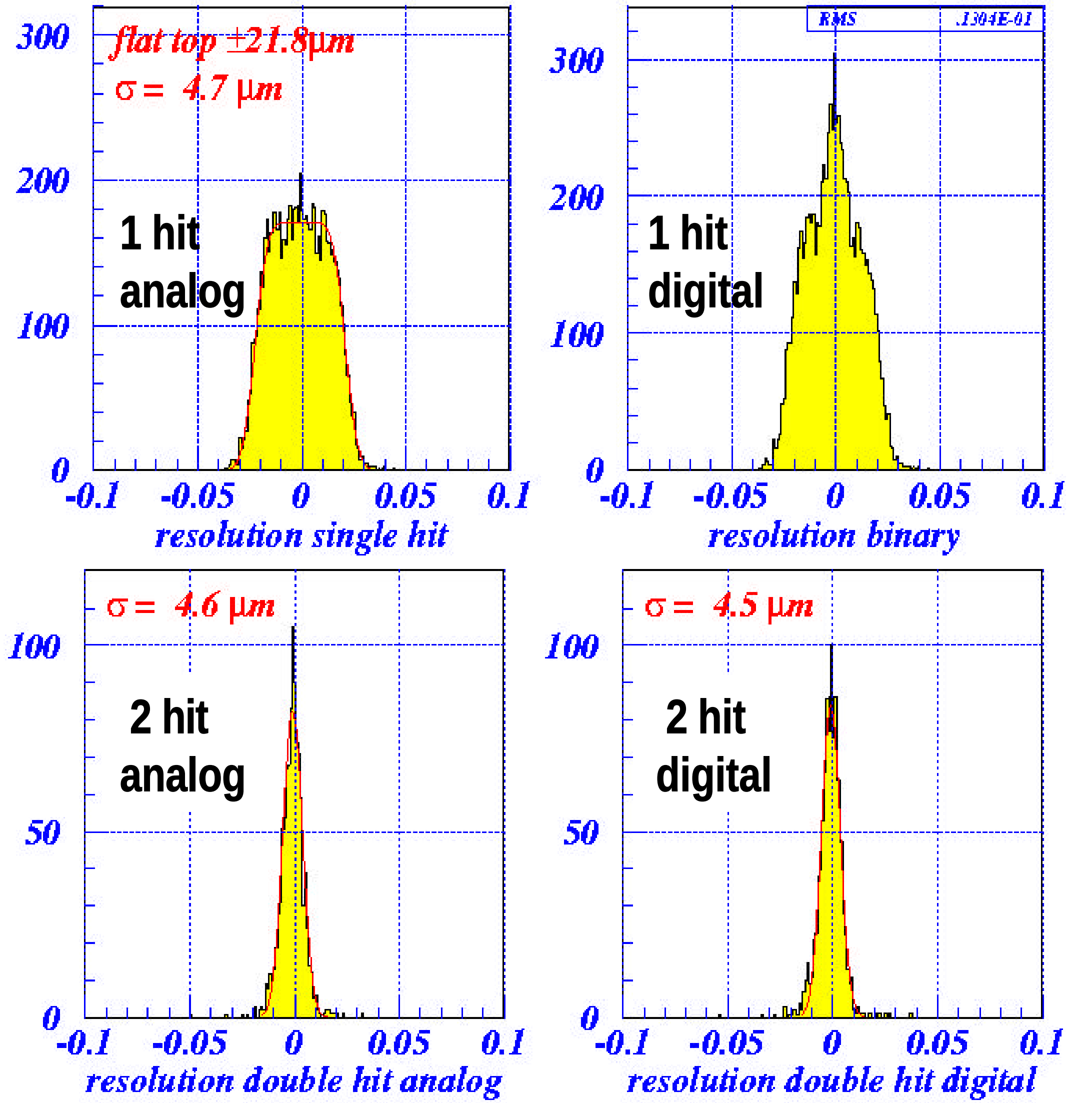


- Spot of ^{241}Am-source on two neighboring chips of a module
- Module without MCC: chips were illuminated one after the other

spatial resolution in test beam

- Consider short pixel dimension:

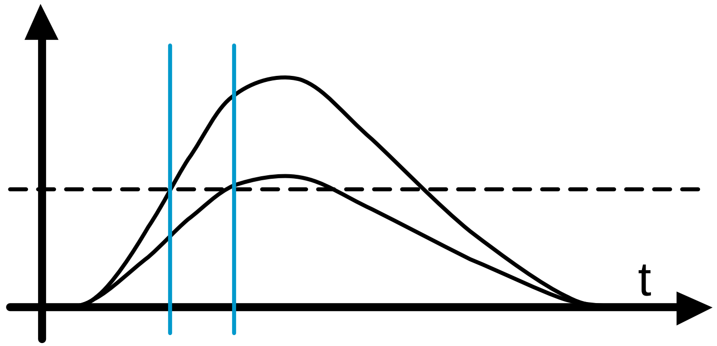


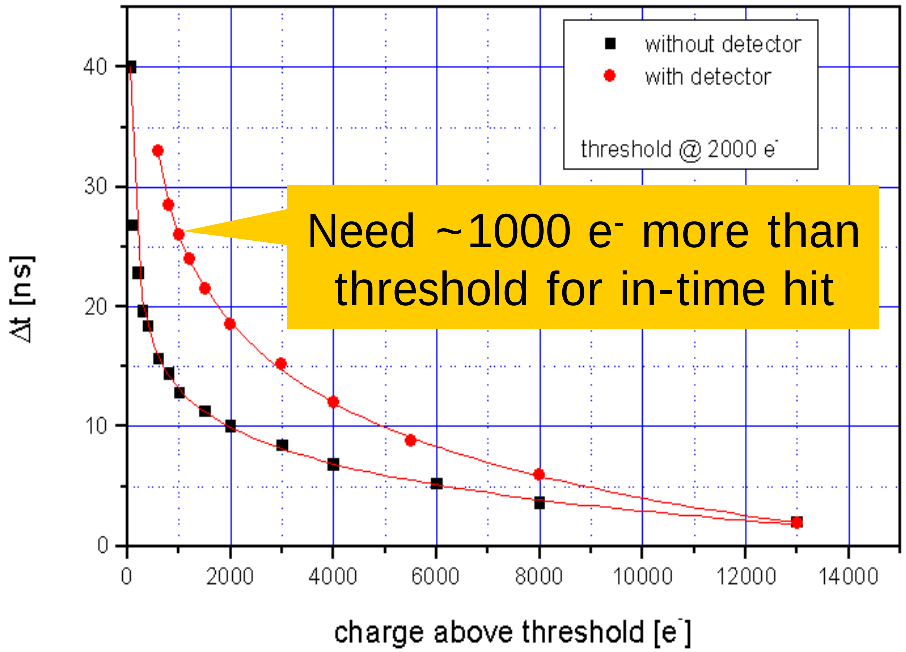


- σ_{1hit} = 22µm, σ_{2hit}=5µm
- σ_{all} = 13µm
  after irradiation: 14.5µm = 50µm/√12
- Less 2 hit clusters after irradiation
- No improvement with analog info!

Time Walk

- Detector is a capacitive load
  - ⇒ preamplifier has slow rise time (limited by power!)
  - ⇒ hits only slightly above threshold fire discriminator later
  - ⇒ hit is lost if delay > 25ns

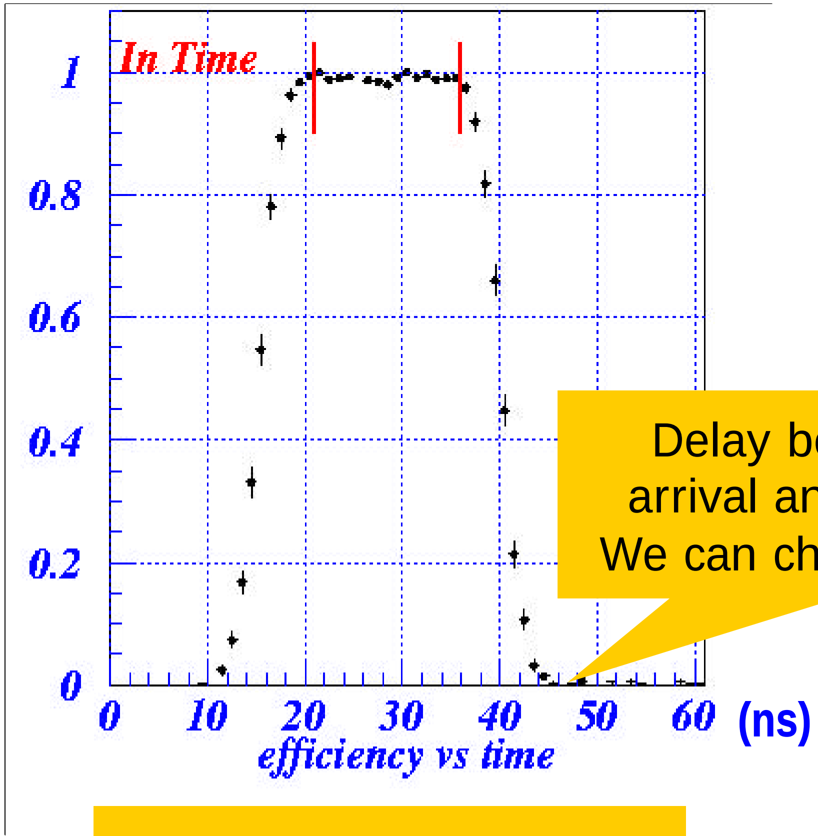




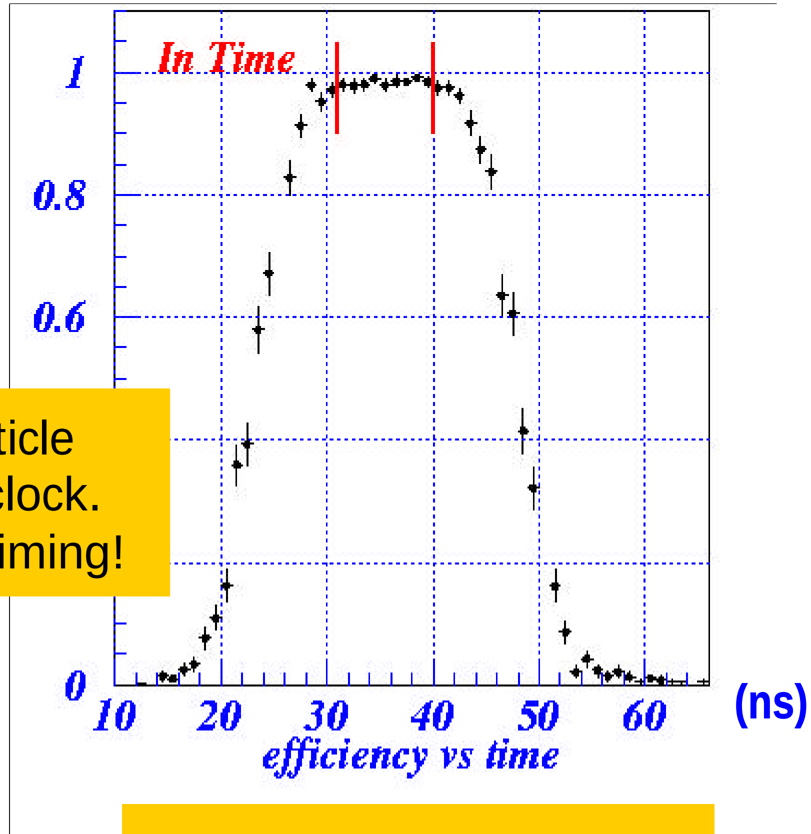
- This is one of our biggest problems. Must still check performance of FEI.
- Possible improvements: digital correction (FEI), zero crossing

Track Efficiency

- Despite marginal time walk, efficiency is ok after irradiation !
- Here: Sensor is moderate p-spray with bias grid. Chip threshold is 3000 e^-



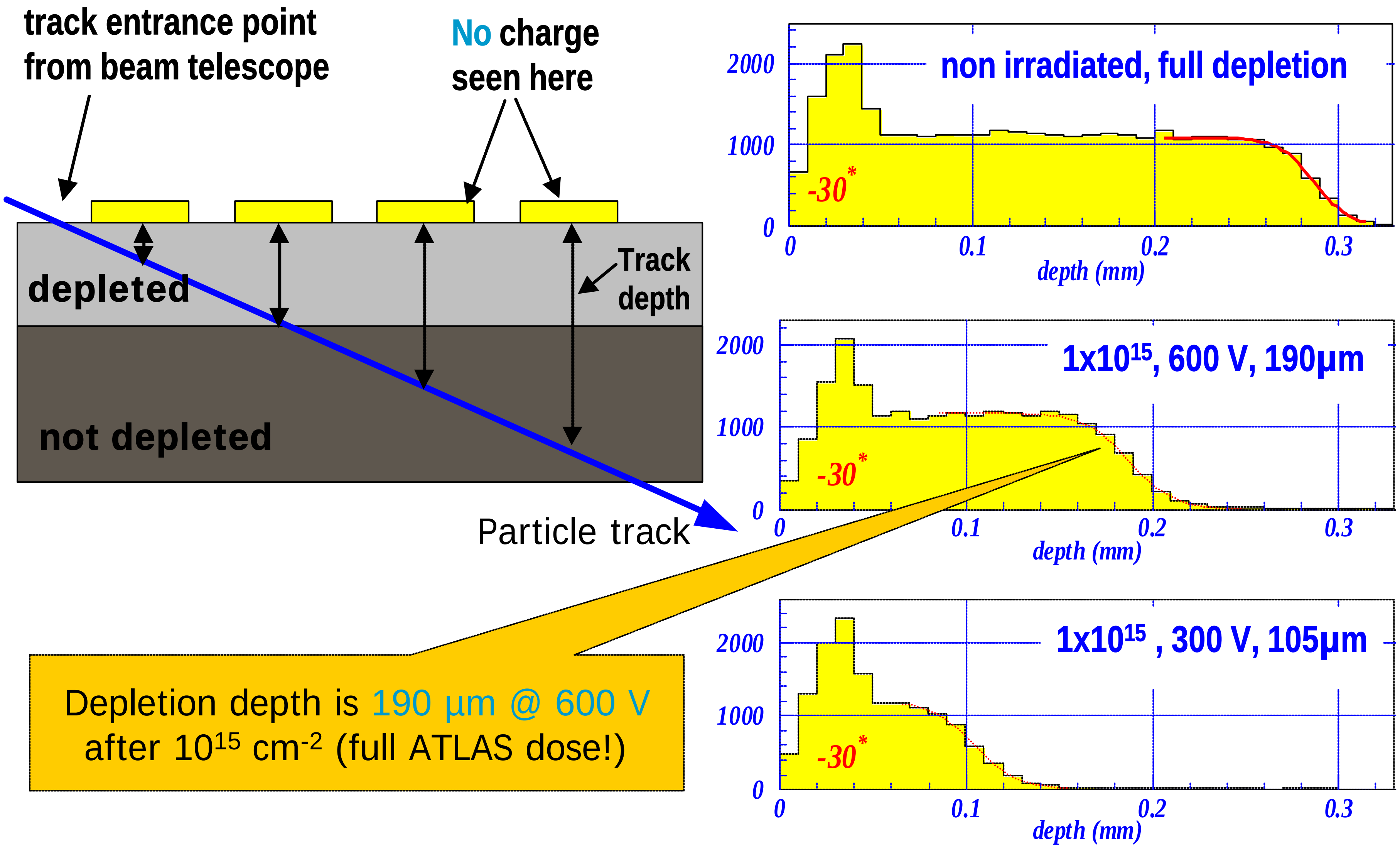
Delay between particle arrival and 40 MHz clock. We can choose best timing!



Non-irradiated
efficiency = 99.1%

Irradiated (10^{15} $n_{eq}cm^{-2}$)
efficiency = 98.4%

Depletion Depth after irradiation



Depletion depth is 190 µm @ 600 V after 10^{15} cm^{-2} (full ATLAS dose!)

ATLAS pixel: Status

We are (nearly) ready to build the detector

- sensors are very mature & are ordered
- FEI radiation hard electronics (0.25µm): performance is good, radiation hardness has been confirmed
- bump bonding: process matured over 4 years
- all module production steps are established
- staves, disks and global support are being produced

Further development is needed for

- cables for power & signals
- connections at module, patch panels etc.
- signal transmission ICs