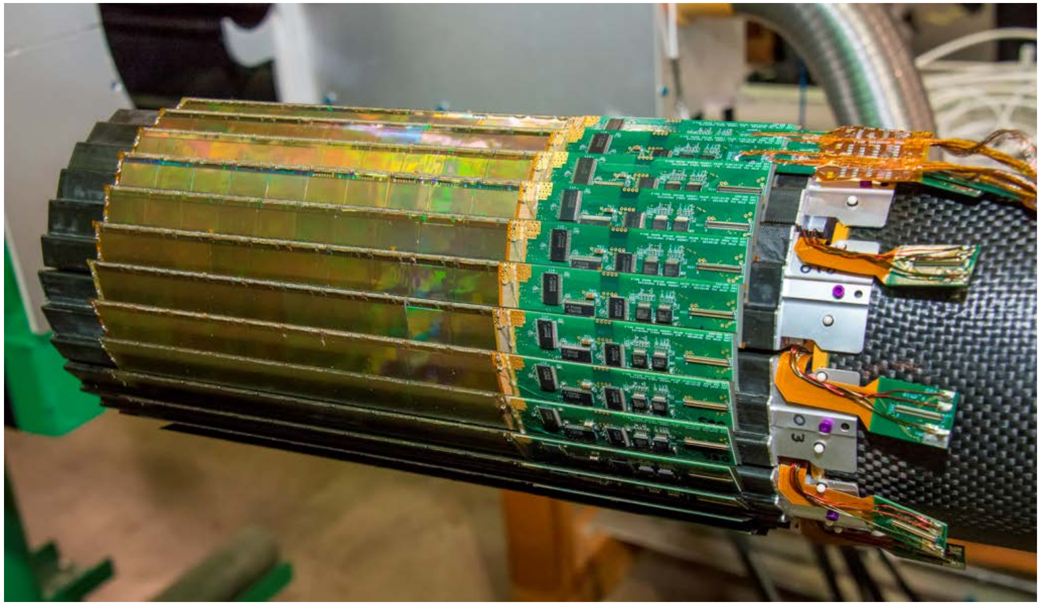
MAPS-based Vertex Detectors: Operational Experience in STAR and Future Applications



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Vertex2017 – The 26th International Workshop on Vertex Detectors
Las Caldas – Oviedo – Asturias – Spain 10-15 September 2017

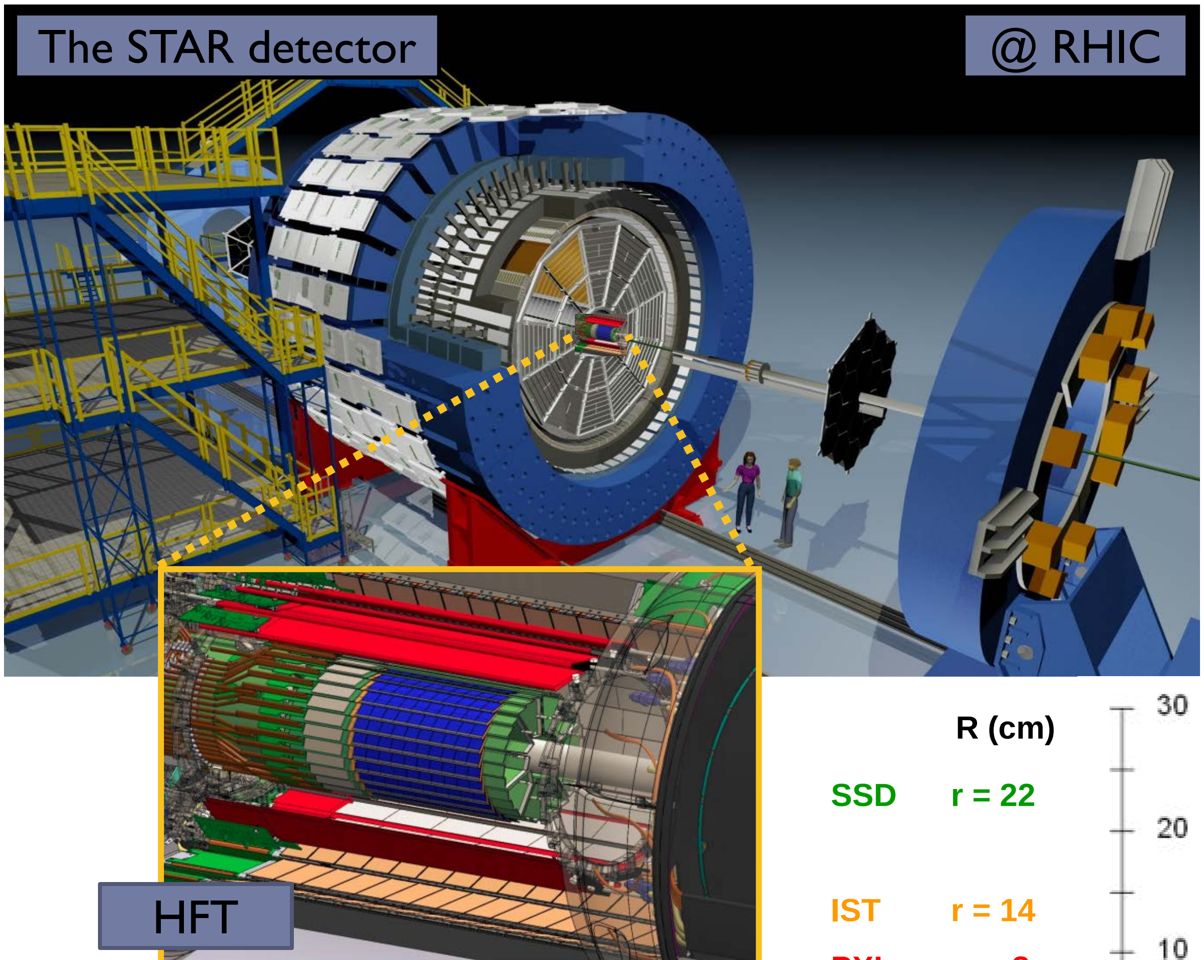
Outline

- First MAPS-based Vertex detector:
  - STAR HFT
    - Design
    - Operations experience
    - Performance and Physics
- Next generation MAPS:
  - ALICE ITS Upgrade
  - sPHENIX MVTX

The STAR Heavy Flavor Tracker

Extend the measurement capabilities in the *heavy flavor* domain, good probe to QGP:

- Direct topological reconstruction of charm hadrons (e.g. $D^0 \rightarrow K\ \pi,\ c\tau \sim 120\ \mu m$)



Need to resolve displaced vertices in high multiplicity environment

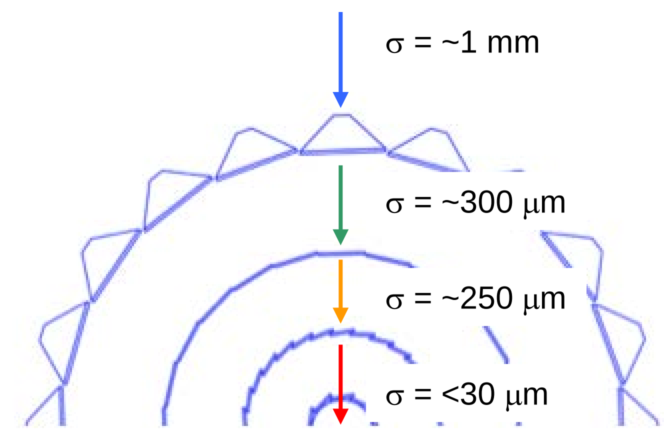
TPC – Time Projection Chamber (main tracking detector in STAR)

HFT – Heavy Flavor Tracker

- **SSD – Silicon Strip Detector**
- **IST – Intermediate Silicon Tracker**
- **PXL – Pixel Detector**

Tracking inwards with gradually improved resolution:

	R (cm)
SSD	r = 22
IST	r = 14
PXL	r_2 = 8
	r_1 = 2.8



PXL Design Parameters

DCA Pointing resolution	(10 ⊕ 24 GeV/p·c) μm
Layer locations	Layer 1 at 2.8 cm radius Layer 2 at 8 cm radius
Pixel size	20.7 μm X 20.7 μm
Hit resolution	3.7 μm (6 μm geometric)
Position stability	5 μm RMS (20 μm envelope)
Sensor thickness	50 μm
Power dissipation	170 mW/cm^2
Material budget first layer	X/X_0 = 0.39% (Al conductor cable)
Integration time (affects pileup)	185.6 μs
Radiation environment	20 to 90 kRad / year $2*10^{11}$ to 10^{12} 1MeV n eq/cm^2
Rapid detector replacement	< 1 day

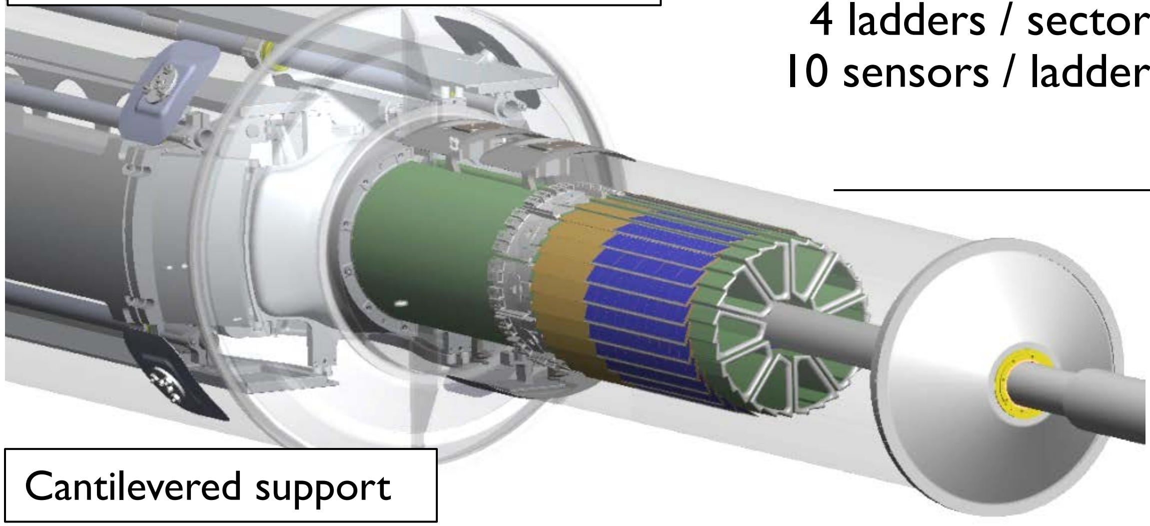
356 M pixels on ~0.16 m^2 of Silicon

PXL System Overview

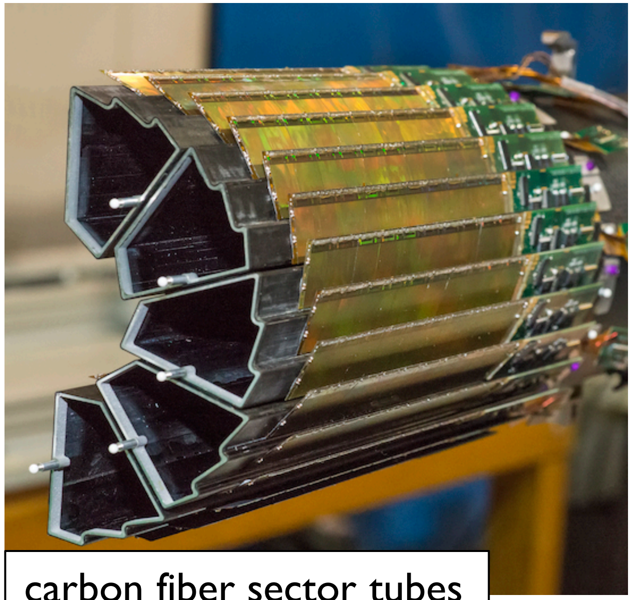
Mechanical support with kinematic mounts (insertion side)

10 sectors total
5 sectors / half
4 ladders / sector
10 sensors / ladder

Highly parallel system



Cantilevered support



carbon fiber sector tubes

Material budget on the inner layer
- Thinned sensor: 50 µm - 0.068% X_0
- Aluminum-conductor cable (32 µm-thick traces) - 0.128% X_0
- Carbon fiber stiffener (125 µm) and sector tube (250 µm) - 0.193% X_0
- Air cooled

0.388% X_0

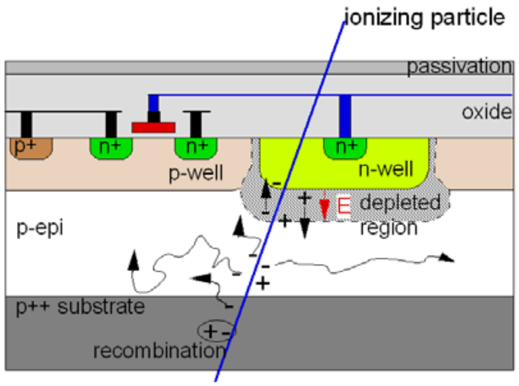
Ladder with 10 MAPS sensors (~ 2×2 cm each)

The PiXeL detector (PXL)

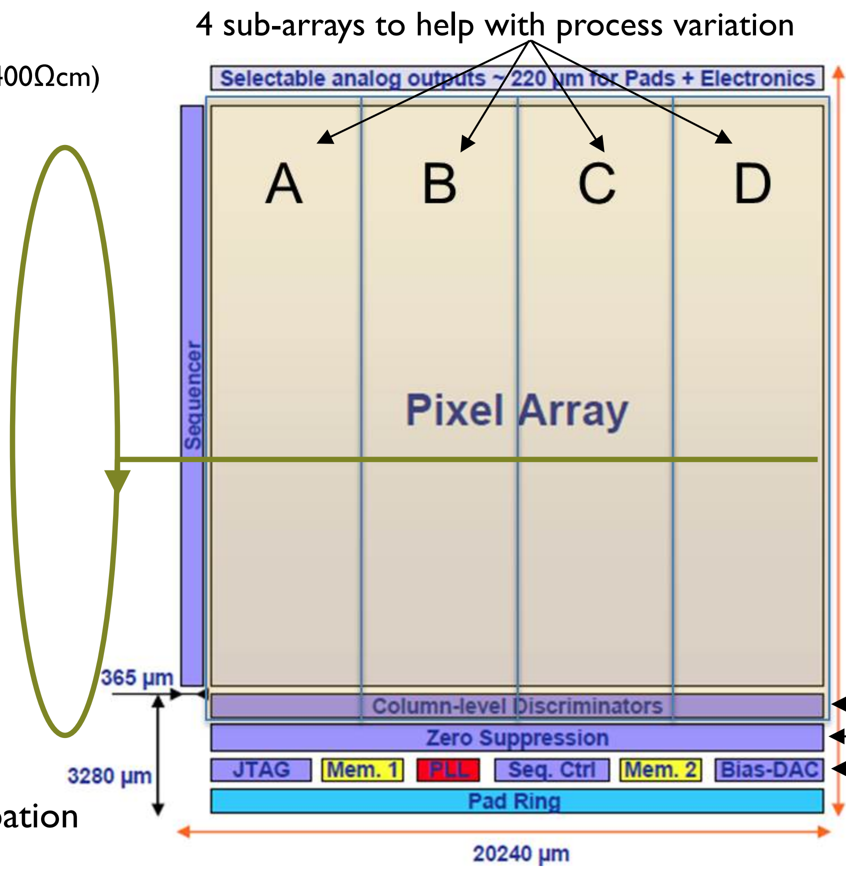
First vertex detector at a collider experiment based on ***Monolithic Active Pixel Sensor*** technology

PXL MAPS sensor

- *Ultimate-2:* third **MIMOSA-family** sensor revision developed for PXL at IPHC, Strasbourg
- ***Monolithic Active Pixel Sensor*** technology



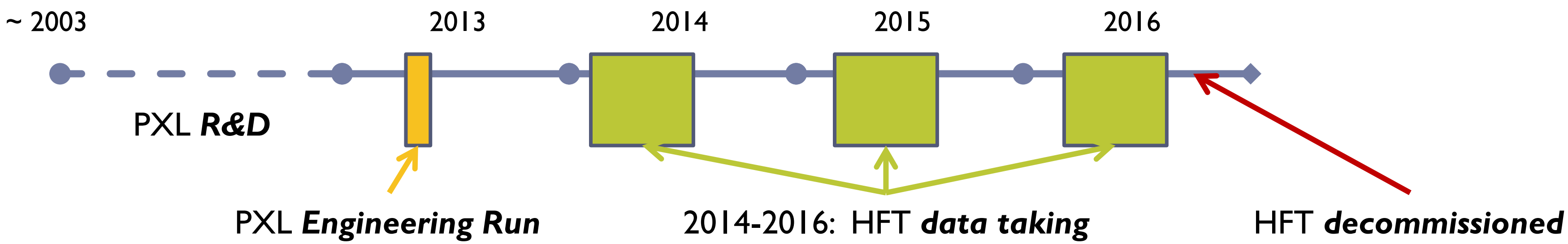
- High resistivity p-epi layer (400Ωcm)
  - Reduced charge collection time
  - Improved radiation hardness
- S/N ~ 30
- MIP Signal ~ 1000 e-
- **Rolling-shutter readout**
  - A row is selected
  - For each column, a pixel is connected to discriminator
  - Discriminator detects possible hit
  - Move to next row
- 185.6 μs integration time
- ~170 mW/cm² power dissipation



- **Pixel matrix**
  - 928 rows * 960 columns = ~1M pixel
  - In-pixel amplifier
  - In- pixel Correlated Double Sampling (CDS)
- **Digital section**
  - End-of-column discriminators
  - Integrated zero suppression (up to 9 hits/row)
  - Ping-pong memory for frame readout (~1500 w)
  - 2 LVDS data outputs @ 160 MHz

- STAR PXL Operations,
  Performance,
  Physics Achievements

PXL timeline and operations



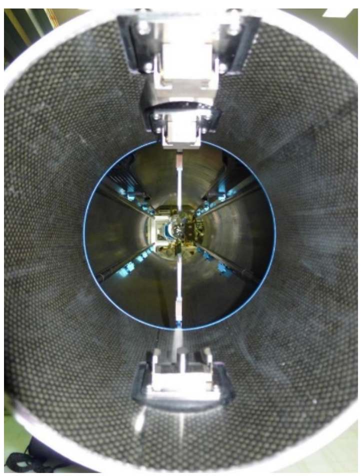
- 2013 **Engineering Run** (3 prototype sectors) allowed discovering and fixing:
  - Shorts between power and GND, or LVDS outputs
  - Mechanical interference in the driver boards on the existing design
  - Missing power control, monitoring and overcurrent thresholds functionalities

- 2014-2016 **Physics Runs**: PXL Operations
  - Hit multiplicity: up to 1000/inner-sensor
  - Typical trigger rate: 0.8-1 kHz
  - Dead time up to ~6%
  - Latch-up reset events: 2 latch-up/min
  - 2014 Run: ~ 1.2 Billion Au+Au
  - 2015 Run: ~ 1 Billion p+p , ~ 0.6 Billion p+Au
  - 2016 Run: ~ 2 Billion Au+Au , 0.3 Billion d+Au

  } Minimum bias events in PXL acceptance @ $\sqrt{s_{NN}}$ = 200 GeV

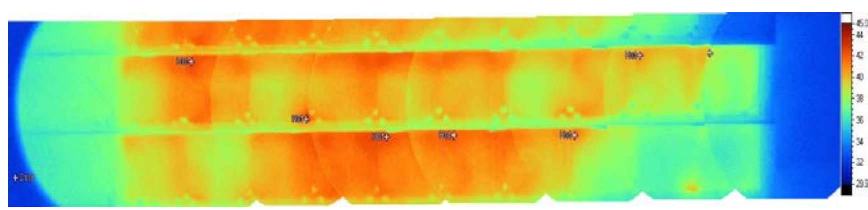
Operational Aspects

- Operational **latch-up protection and voltage control** limited the effect of LU-related sensor damage *(more later in this talk)*
- **Detector reset** on a 15 minute schedule limited SEU-related data corruption
- **Mechanics**
  - The detector halves maintained survey pixel positions after insertion and during operational heating and in the cooling airflow (10 m/s).
  - The rapid insertion and removal mechanism worked well, allowing removal and replacement operation of a 2nd detector in one day.
- **Air cooling** worked very well, typical variation in sensor temperature over the runs was within 1-2 degree C.



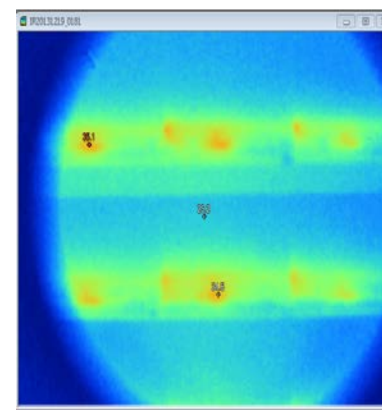
PXL Kinematic mounts

Sector vibration in the radial direction scales as:	$flow^2$
Sector vibration at full flow:	5 µm RMS
Sector DC displacement scales as:	$flow^2$
Sector moves in at full flow: **(Stable displacement)**	25 µm - 30 µm
Sector moves in when ladders powered: **(Stable displacement)**	3 µm - 8 µm



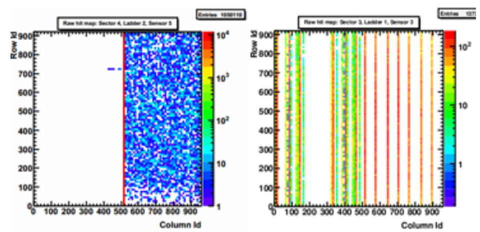
Composite IR image of PXL test ladders

IR image of production PXL ladders. Max ΔT is 12° C from ambient.

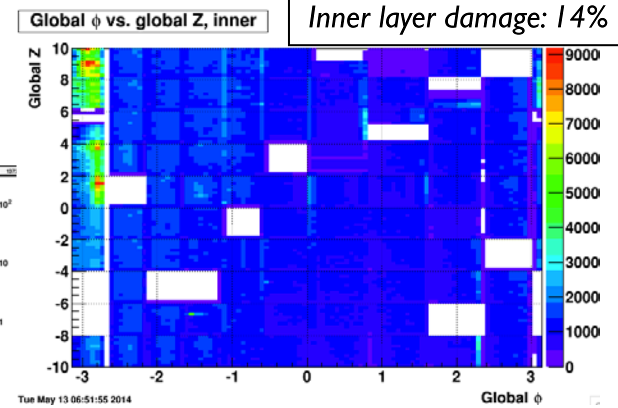


Operational issues: Latch-up damage

- Unexpected damage seen on 15 ladders in the STAR radiation environment in 2014 Run first 2 weeks
  - Digital power current increase
  - Sensor data corruption
  - Hotspots in sensor digital section
  - Correlated with *latch-up* events
  - Limited with operational methods



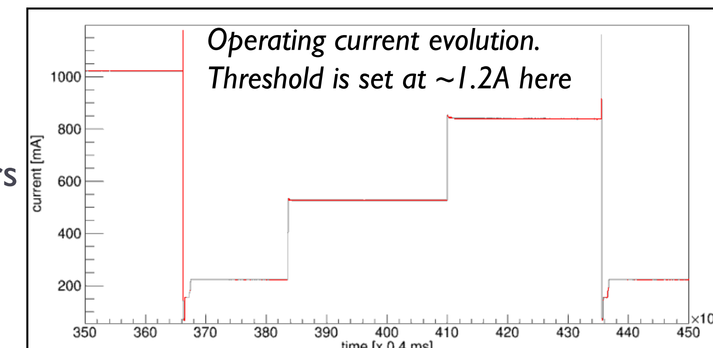
Inner layer damage: 14%



- Latch-up tests at *BASE facility* (LBL) to measure latch-up cross-section and reproduce damage
  - 50 μm & 700 μm thick, low and high resistivity sensors; PXL ladders
  - Irradiation with heavy-ions and protons

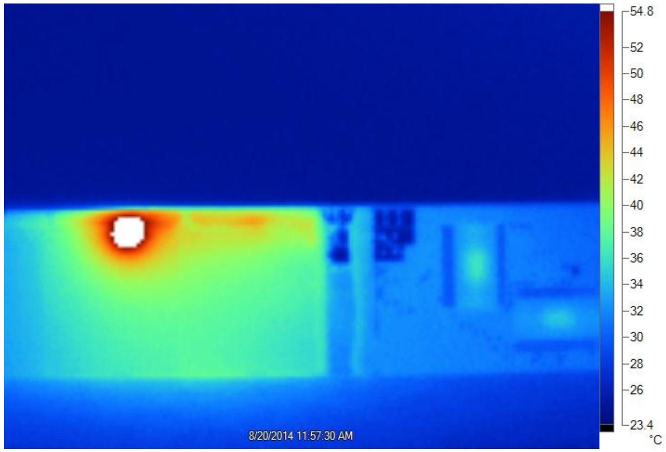
Latch-up phenomenon:
- Self feeding short circuit caused by single event upset
- Can only be stopped by removing the power

- Results and observations
  - Current limited latch-up states observed (typically ~300 mA)
  - Damage reproduced only with HI on PXL 50 μm thinned sensors
  - Latch-up protection at 80 mA above operating current
  - Periodic detector reset to clear SEU



Latch-up test damage analysis

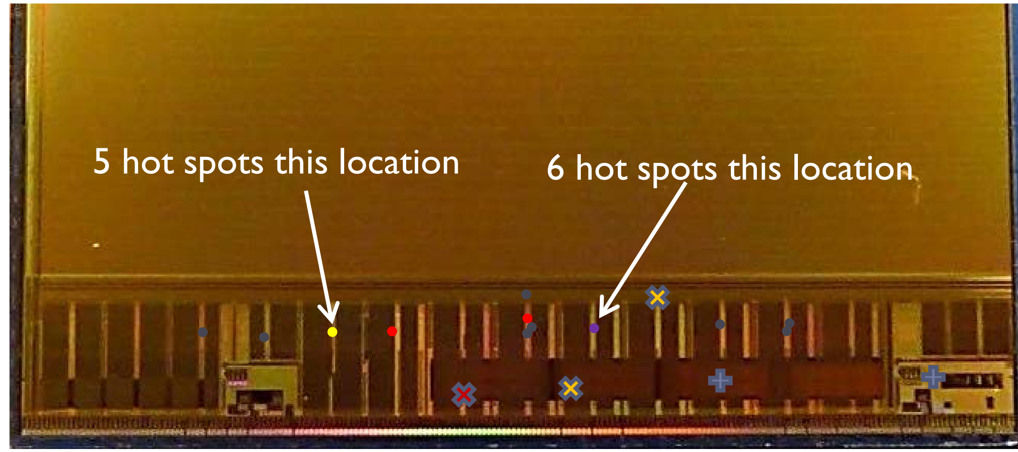
Hot spot showing damage to sensor #2 on run 14 ladder

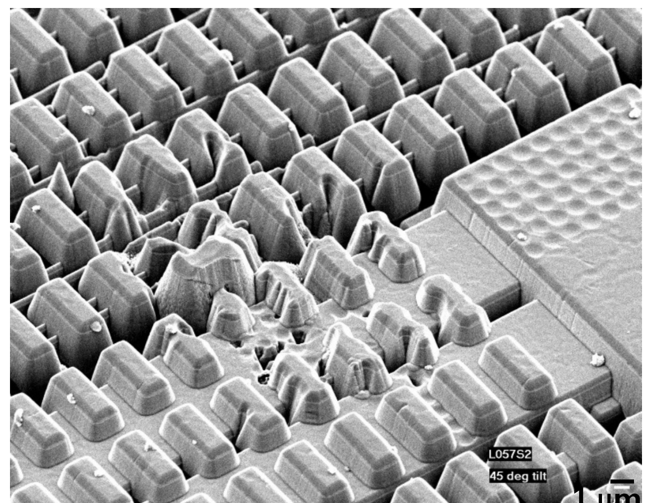


50 um thinned silicon
Temperatures from 55-100 C

- **Full thickness sensors were tested** for LU during development: measured cross section consistent with LU events recorded on the detector
- **Damage cross section is too low** to easily measure with individual sensors based testing

Hotspots tend to favor particular structures (isolated buffers with specific structure pitch)





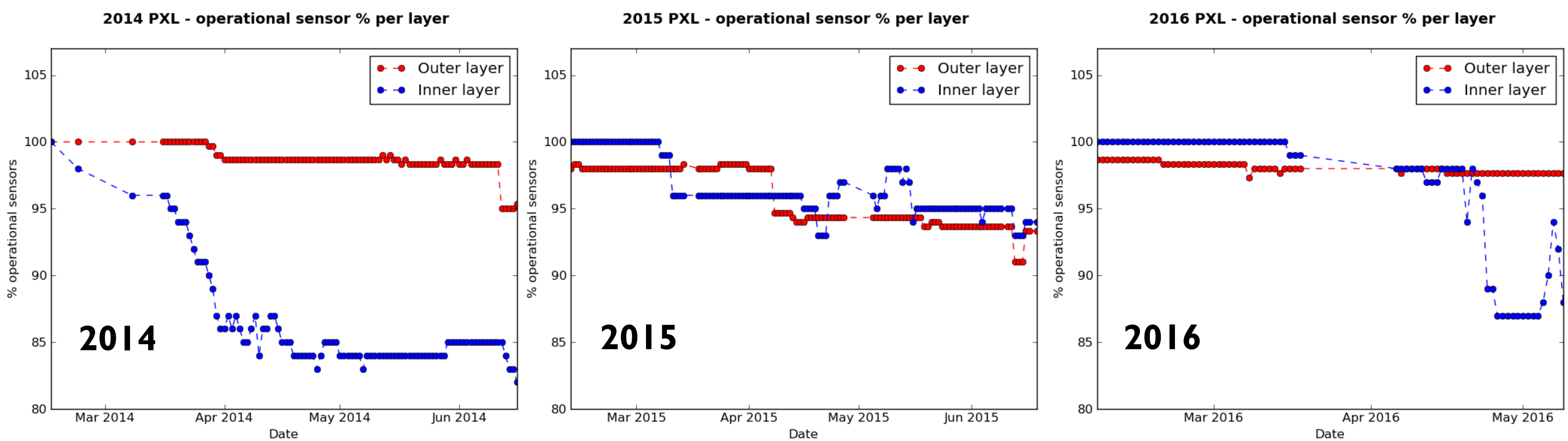
PXL sensor layers deconstructed (plasma etching technique) and viewed with SEM (@BNL Instrumentation Division)

The layers appear to be melted

Latch-Up Damage evolution

Run	Good sensors on Inner Layer		Good sensors on Outer Layer		*Comment*
	installation	**end of run**	installation	**end of run**	
2014	100%	82%	100%	95%	LU damage, most of it in the first 15 days of operations
2015	99%	94%	98%	96% *(93%)**	* = Lost control of an outer ladder (10 good sensors off)
2016	100%	95% *(87%)+*	99%	98%	+ = Current instability on inner ladder (8 good sensors off)

Good sensor = sensor with >95% active channels and uniform efficiency



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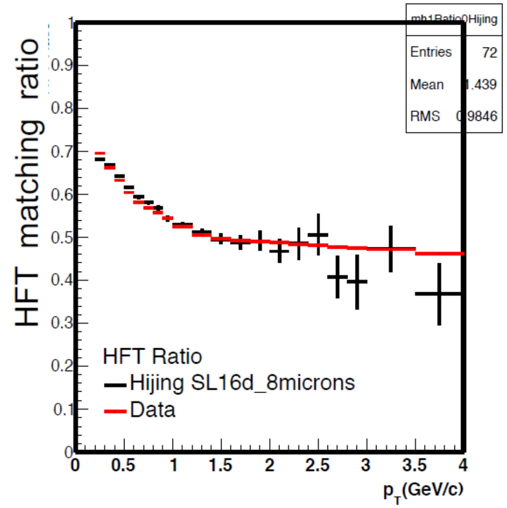
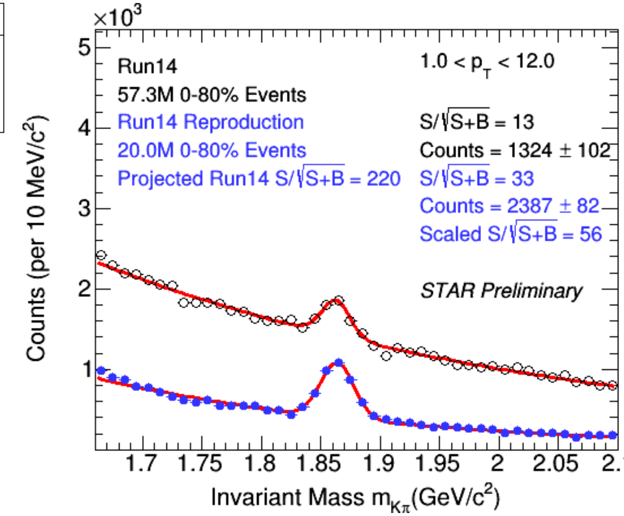
Software/Firmware issues

- Reconstruction software issue - 2014 data production
  - A bug in the **reconstruction** software led to an **efficiency loss** in the reconstructed 2014 Run data, affecting the preliminary STAR results
  - After fixing the bug, the new data reconstruction and analysis showed a significant improvement in the tracking performance which now matches the simulation → *~4x Significance*

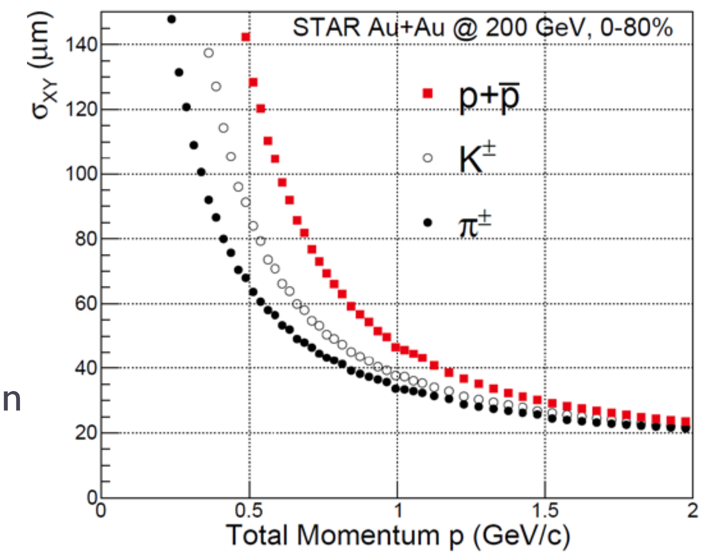




- Readout firmware issue - 2015 data, matching inefficiency
  - A subtle bug introduced by a change in the **PXL RDO firmware** led to an efficiency loss in the 2015 Run p+p data
  - **Feedback and data QA tools:**
    - The extensive tests with pattern data and the calibration were inadequate
    - A fast-offline tracking QA was put in place only after the 2015 Run
  - **Fix:** A post-run investigation based on external **sensor illumination with LED** allowed for firmware debugging and fixing

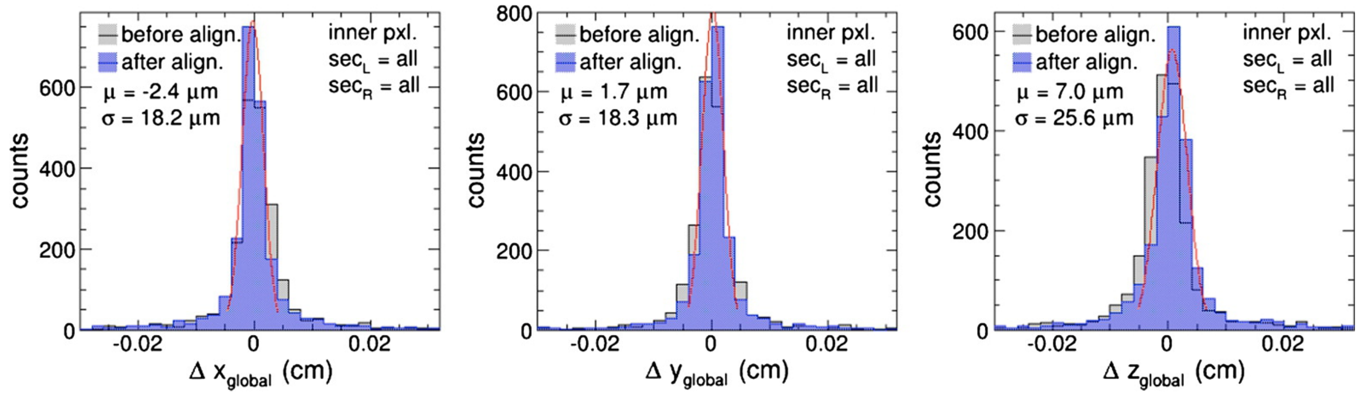
HFT Performance from 2014 data

- Distance of Closest Approach (DCA) resolution - design requirements exceeded
  - ~ 50 μm for 750 MeV/c Kaons
  - ~ 30 μm for p > 1 GeV/c



- Sensor detection efficiency:
  - 97.2% average estimated with cosmic rays before the Run

- Alignment
  - Residuals distribution after alignment shows σ ≤ 25 μm



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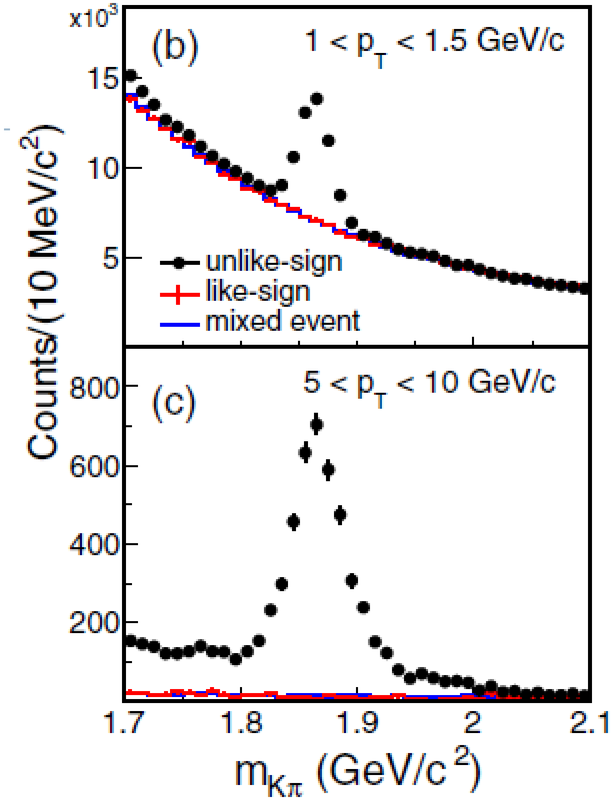
HFT Physics achievements

- Physics of D-meson production
  - High significance signal
  - Nuclear modification factor R_{AA}
  - Collective flow v_2

Sample: ~900 M *Au+Au* collisions $\sqrt{s_{NN}}$ = *200GeV*



- ***$D^0 \rightarrow K + \pi$***
  - Significance $S/\sqrt{S+B} \sim 220$

- ***$D_S^{\pm} \rightarrow \phi(K^+ + K^-) + \pi^{\pm}$***
  - Significance $S/\sqrt{S+B} \sim 25$

- ***NEW!!!* First measurement of Λ_c baryons in HI collisions**
  - $\Lambda_c^{\pm} \rightarrow p^{\pm} K^{\mp} \pi^{\pm}$ $c\tau \sim 60\mu m$ BR = 5 %
  - Experimentally challenging to measure in heavy-ion collisions
    → Combinatorial background is greatly suppressed
  - Significance: $S/\sqrt{S+B} \sim 5.2$ (10-60% centrality, p_T: 3–6 GeV/)
  - Λ_c/D^0 ratio compatible with baryon-to-meson ratios of light hadrons

STAR PXL Project: Strengths and Weaknesses

Strengths

- MAPS technology features
- Sensor and Readout System developments strictly coupled
- Engineering run, crucial for the program
- ~Full control on the production

⟶ **Success!** { Performance exceeded expectations
Access the charm domain

Weaknesses

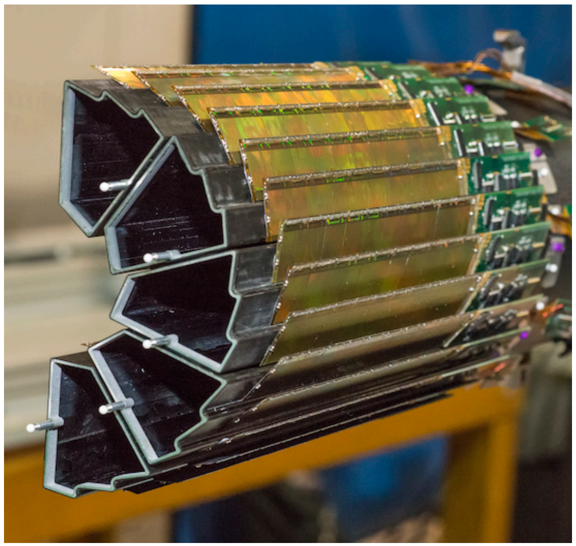
- The technology was new for a collider environment
- Short (3-years) physics program
- Sensor integration time too long to access the bottom domain

⟶ **Future:** ALICE ITS Upgrade, sPHENIX MVTX

Evolution of MAPS-based Vertex Detector

2014-2016 | 2021+

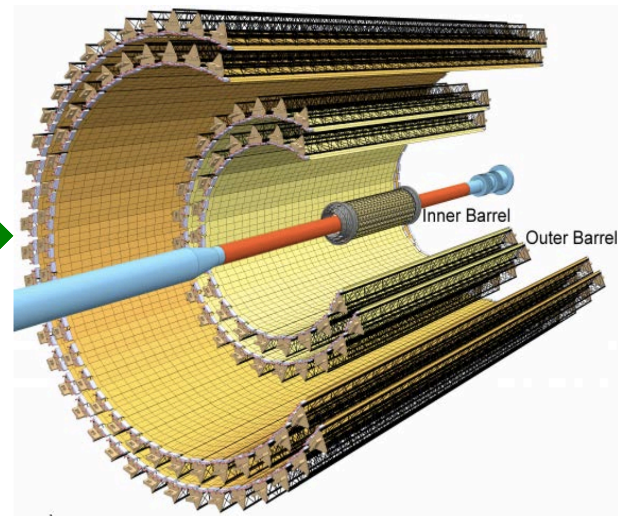
STAR HFT/PXL



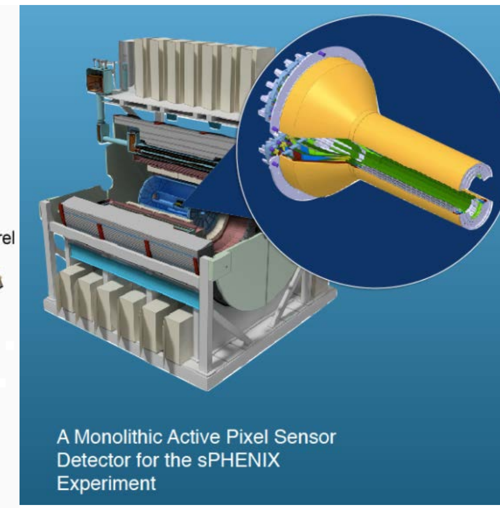
Integration time: **186 µs**

Thickness first layer: 0.4%X_0

ALICE ITS Upgrade



sPHENIX MVTX



Integration time: **<20 µs**

Thickness first layer: 0.3%X_0

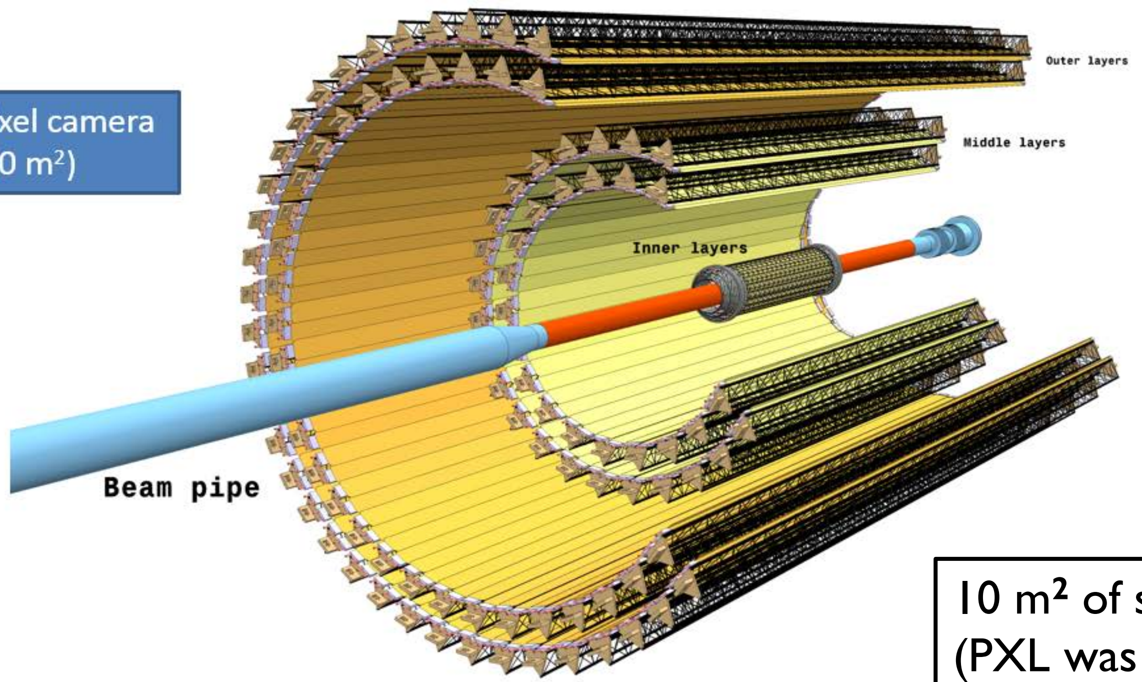
Next generation MAPS detector used for ALICE ITS Upgrade and proposed for sPHENIX MVTX:
Thin MAPS detector with much shorter integration time
-> Significantly reduced background hits -> Much improved tracking efficiency

@*LHC*: ALICE ITS Upgrade

from HybridPixels/Drifts/Strips to MAPS

→ *see A.Alici on the Current ITS (this workshop)*

12.5 G-pixel camera
(~10 m²)



10 m^2 of silicon
(PXL was 0.16 m^2)

7-layer barrel geometry based on MAPS

r coverage: 23 – 400 mm

η coverage: $|\eta| \leq 1.22$
for tracks from 90% most luminous region

3 Inner Barrel layers (**IB**)

4 Outer Barrel layers (**OB**)

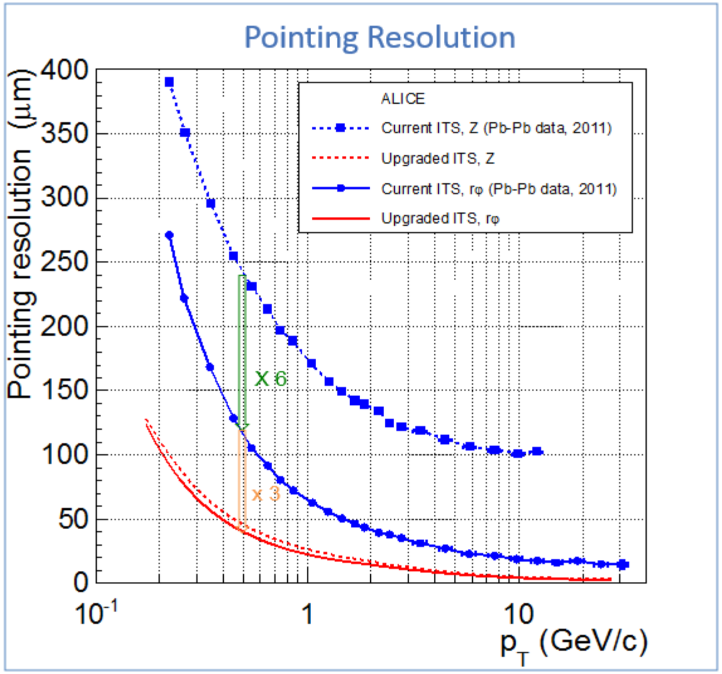
Material /layer : 0.3% X_0 (IB), 1% X_0 (OB)

ITS Upgrade TDR: http://iopscience.iop.org/0954-3899/41/8/087002/

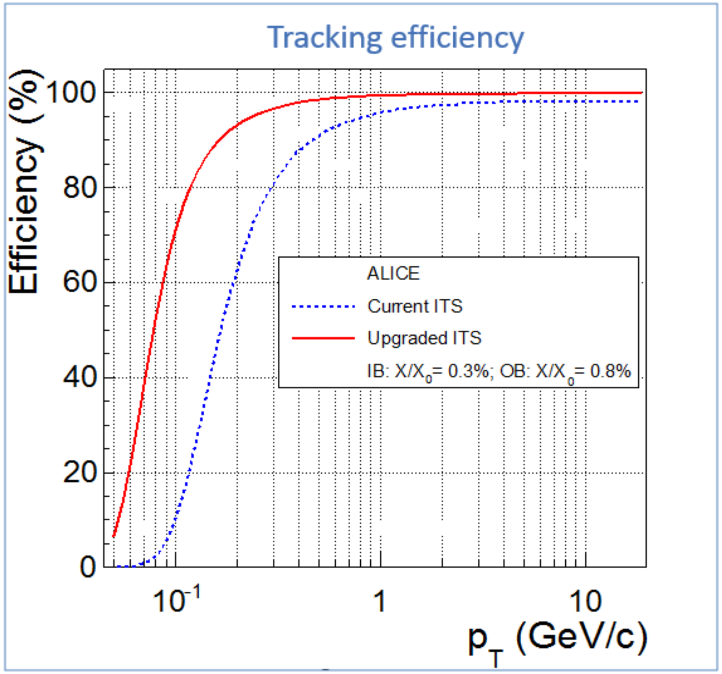
Upgraded ITS Performance

Performance of new ITS (MC simulations)

Impact parameter resolution



Tracking efficiency (ITS standalone)

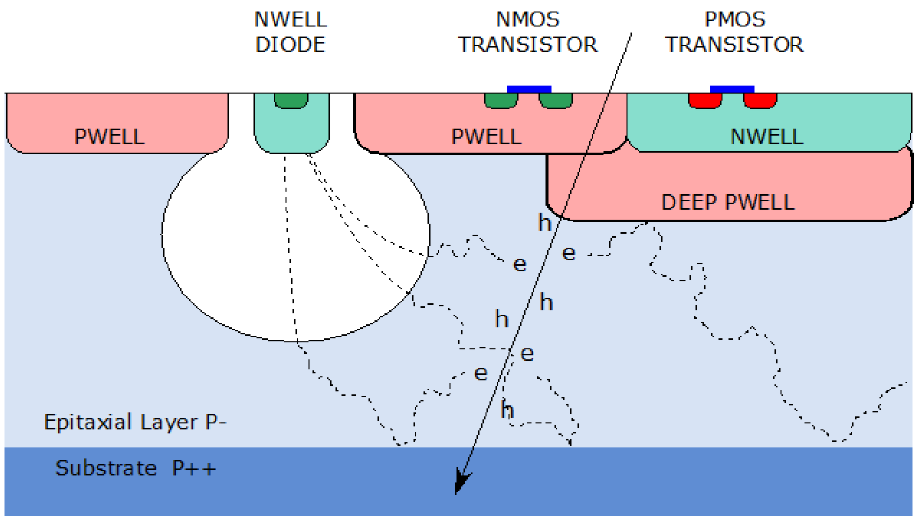


Existing ITS:	Hybrid pixels, drift, strips	$X/X_0 \geq 1\%$ /layer	~120 μm @ 500MeV/c
ITS Upgrade:	All layers are MAPS sensors	X/X_0 ~0.4% /layer	~40 μm @ 500MeV/c

Physics Goals: Improve charm meson study - Access charm baryons, bottom hadrons in Pb-Pb collisions

ITS Pixel Chip – technology choice

CMOS Pixel Sensor using TowerJazz 0.18μm CMOS Imaging Process



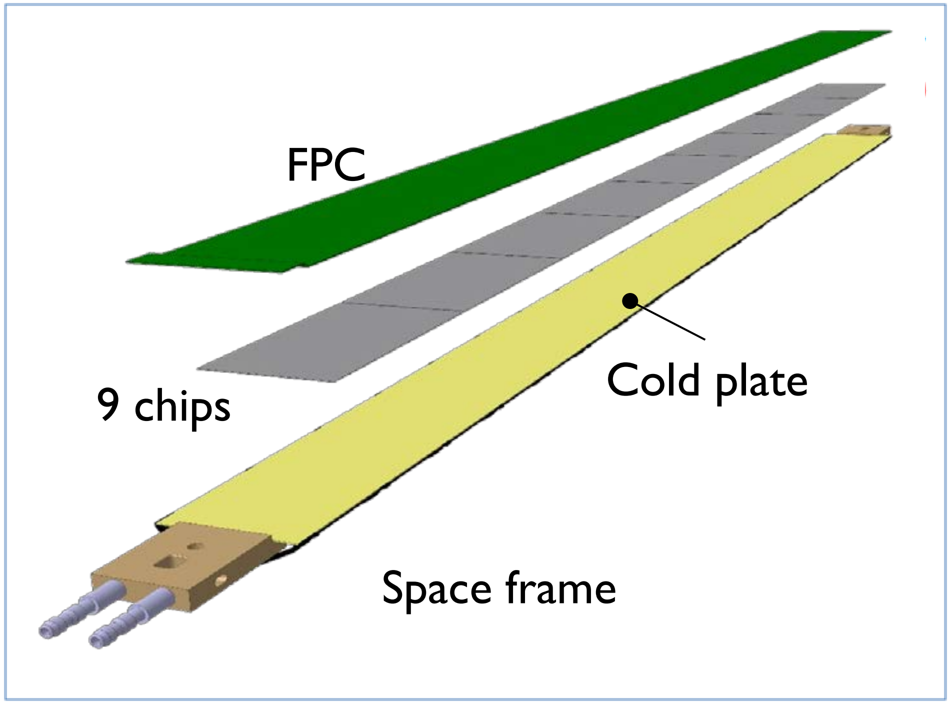
→ *see also R.Tieulent on the ALICE MFT (this workshop)*

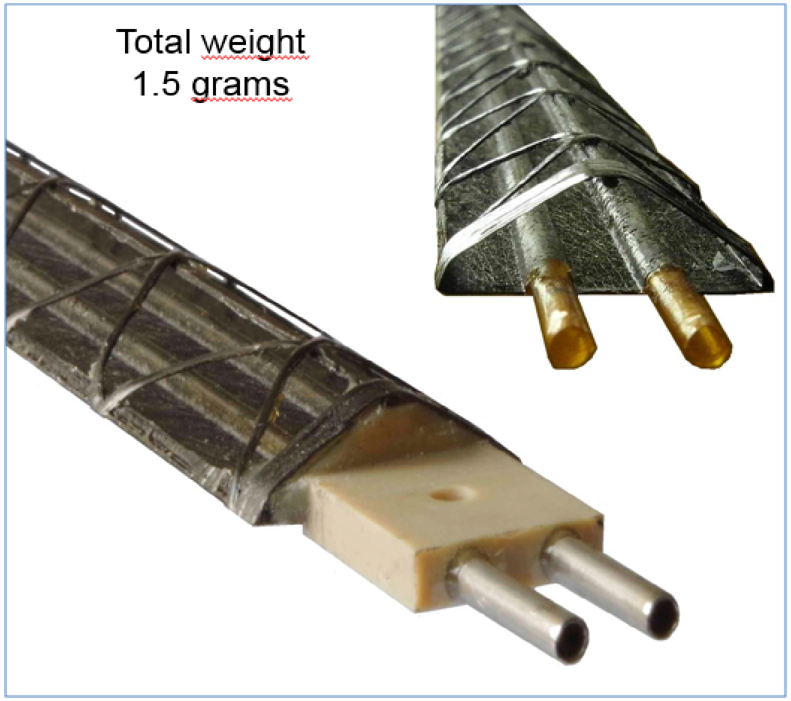
ALPIDE sensor *(developed at CERN)*

- ~28 μm pitch
- Integration time: < 20 μs
- Trigger rate: 100 kHz
- Read out up to 1.2 Gbit/s
- Power: 40 mW/cm^2
- Priority encoder - sparsified readout
- Rad.Tolerant: 700krad -10^{14} 1MeV n_{eq}/cm^2

- High-resistivity (> 1kΩ cm) p-type epitaxial layer (20μm - 40μm thick) on p-type substrate
- Small n-well diode (2-3 μm diameter), ~100 times smaller than pixel => low capacitance
- Application of (moderate) reverse bias voltage to substrate can be used to increase depletion zone around NWELL collection diode
- Quadruple well process: deep PWELL shields NWELL of PMOS transistors, allowing for full CMOS circuitry within active area

New ITS Layout - Inner Barrel Stave



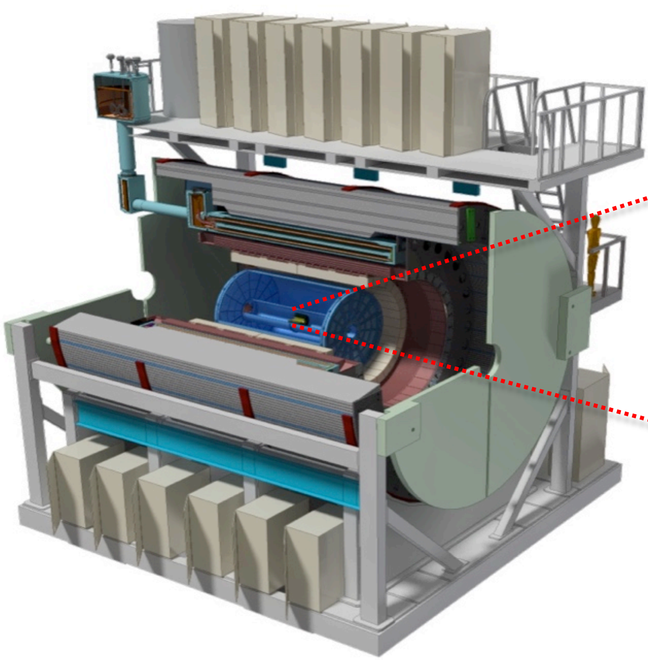


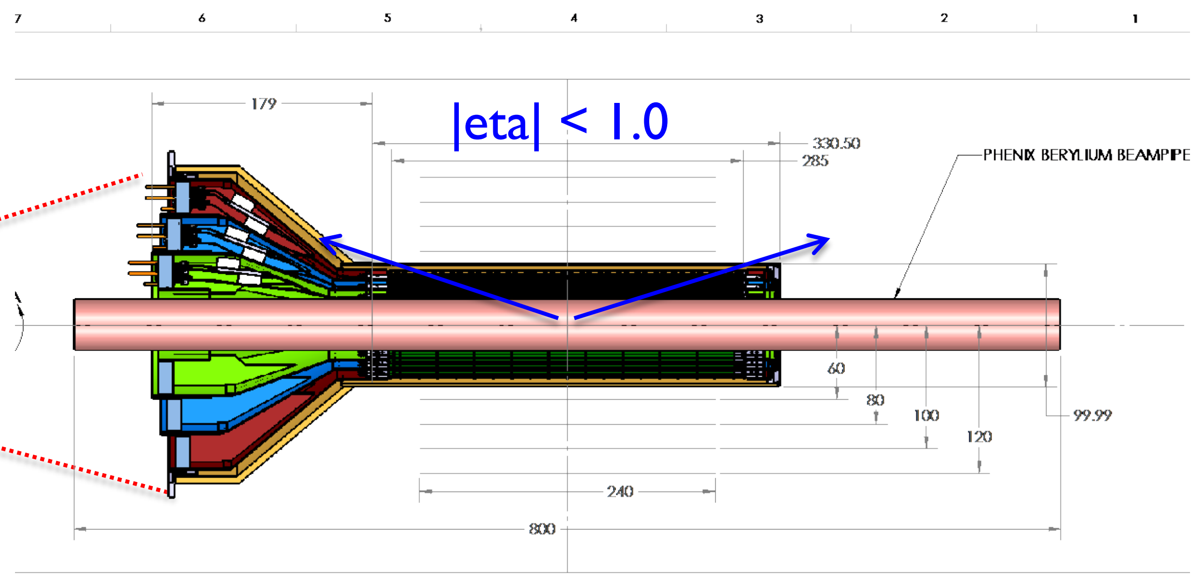
<Radius> (mm): 23,31,39	Length in z (mm): 290
Nr. of staves: 12, 16, 20	Nr. of chips/stave: 9
Nr. of chips/layer: 108, 144, 180	Material thickness: ~ 0.3% X_0
Power density: < 100 mW/cm^2	Throughput (@100kHz): < 80 $Mb/s \times cm^{-2}$

@RHIC: MAPS Vertex Detector (MVTX) for sPHENIX

sPHENIX: next-generation heavy-ion experiment on jets and Upsilons at RHIC
- detailed in NSAC long range plan 2015
- received first approval in Sept. 2016, inner tracker detectors not included in the baseline

MVTX brings new **heavy flavor** physics program to sPHENIX
- open bottom production at mid-rapidity over a broad momentum at RHIC





R = 2.3, 3.1, 3.8cm
L = 27.1cm

Physics-driven Detector Requirements

Physics goal: Access and study open bottom physics at RHIC

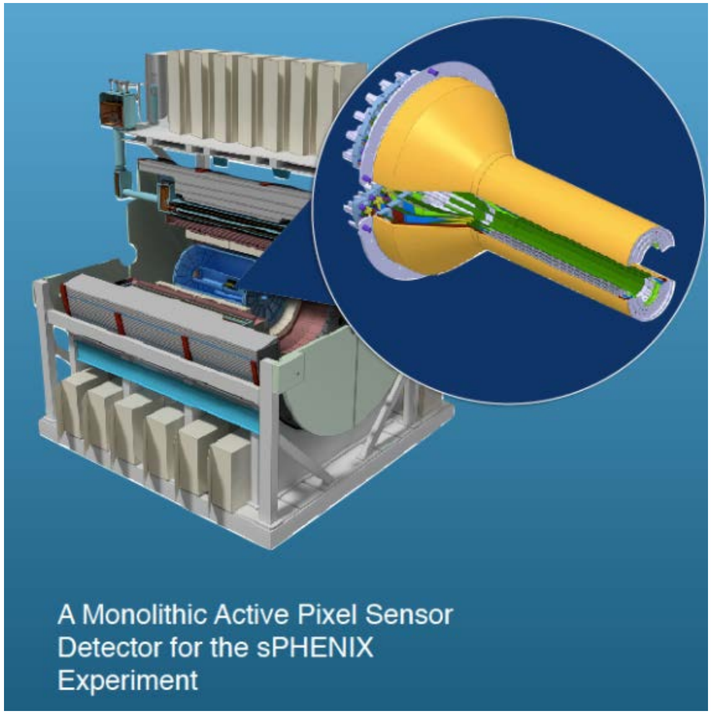
↓

Design goals: Reduce background hits, improve tracking efficiency

↓

Item	Requirements
Acceptance	Vertex $|z| < 10$ cm, $|\eta| < 1$, full azimuthal coverage
Event rate	Matching the sPHENIX DAQ rate of 15 kHz event rate
DCA resolution	< 50 μm for charged pions at $p_T = 1$ GeV/c
Tracking efficiency	$> 60\%$ efficiency for charged pions at $p_T = 1$ GeV/c in central Au+Au collisions

sPHENIX MVTX Proposal



- Technology choice: **MAPS**
  - ALPIDE sensor meets the requirements for MVTX
  - Int. time <20μs, ~28μm pitch, pow. diss. 40mW/cm^2
- Detector layout based on: **ITS Inner Barrel**
- **Leverage the ITS Upgrade R&D for:**
  - Sensor design and production
  - Inner Barrel and Mechanics layout
  - Stave production & test
  - Power system design
  - Readout Units design
- **Specific R&D - Fabrication - Assembly for MVTX**
  - Develop data aggregation/formatting/DAQ interface
  - Adapt and integrate carbon fiber structures design, and fabricate
  - Adapt and fabricate Power System and Readout Units
  - Assemble the detector and integrate in sPHENIX

Proposed MVTX Tasks and Timeline

FY2016 | FY2017 | FY2018 | FY2019 | FY2020 | FY2021 | FY2022

sPHENIX baseline

CD-0 9/2016

CD-1

CD-2/3

Ready for Beam

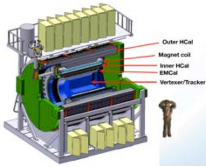
ALICE ITS/IB Production

Key R&D

- Readout R&D
  Mechanics design
- Mechanics
  Integration
  & Prototyping

Production

MAPS Prod. & QA By ALICE @CERN → IB Stave prod.&test @CERN; RU/CRU Prod. @US Carbon Structures @US → Detector Assembly & Test @LBNL → Installation @BNL



+2% +50%

Aim to produce the staves following the ALICE production at CERN

- Produce MAPS chips and Stave Space frames for sPHENIX as part of ALICE production

Conclusions

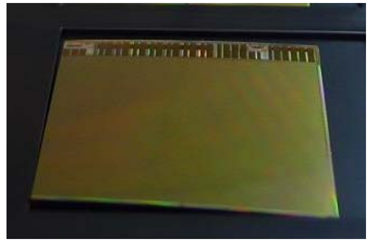
- STAR PXL, first generation MAPS-based detector at a collider experiment, successfully completed the 3-year physics program at RHIC
  - Performance met design requirement, access open charm physics
  - 2013 Engineering Run, short duration program
- MAPS technology proved to be suitable for vertex detector applications
- Next-generation MAPS sensor: ALPIDE
  - Shorter (x10) integration time
  - Higher radiation tolerance
- Next-generation MAPS-based vertex detectors:
  - ALICE ITS Upgrade @LHC *(now entering the production phase)*
  - sPHENIX MVTX @RHIC *(recently proposed)*
    - Reduced background hits, improved tracking efficiency → open bottom physics

Thank you for your attention!

Backup slides

PXL Material Budget

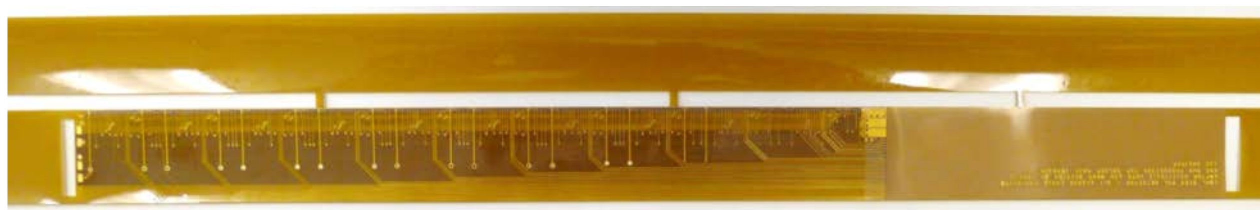
- Thinned Sensor
  - 50 μm
  - 0.068% X_0



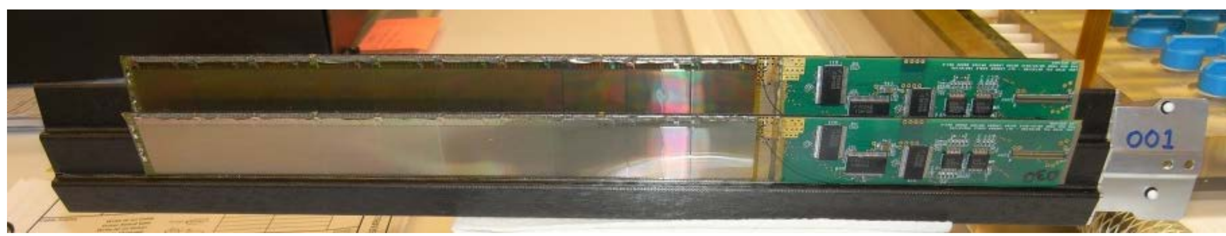
- Curved sensor
- 40-60% yield after thinning, dicing and probe testing
- Fully characterized before installation

- Flex Cable
  - Aluminum-Kapton
  - two 32 μm-thick Al layers
  - 0.128% X_0
    - *Copper* version → 0.232% X_0

- Power and signal lines
- Wire bond encapsulant largest contribution
- Acrylic adhesive to deal with different CTE



- Carbon fiber supports
  - 125 μm stiffener
  - 250 μm sector tube
  - 0.193% X_0



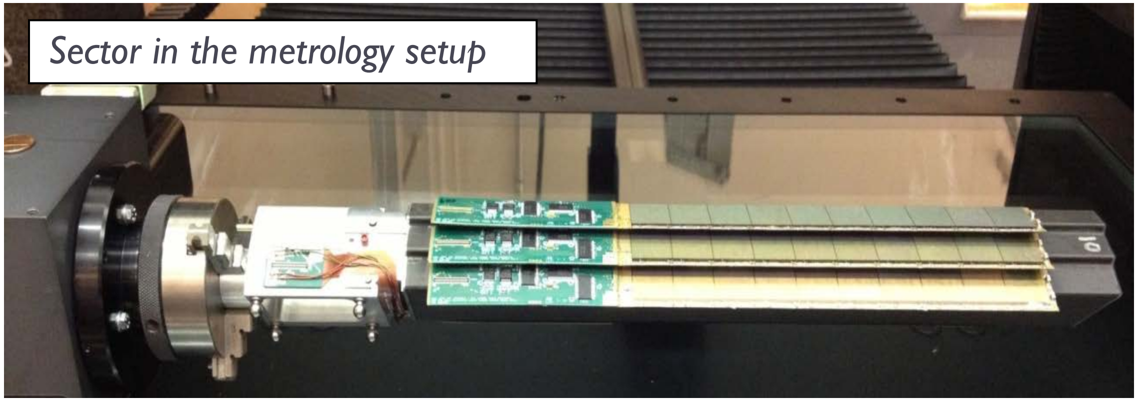
- Cooling
  - Air cooling: negligible contribution

- **Total material budget on inner layer: 0.388% X_0**

(0.492% X_0 for the Cu conductor version)

HFT DCA pointing resolution:
(10 ⊕ 24/p) μm

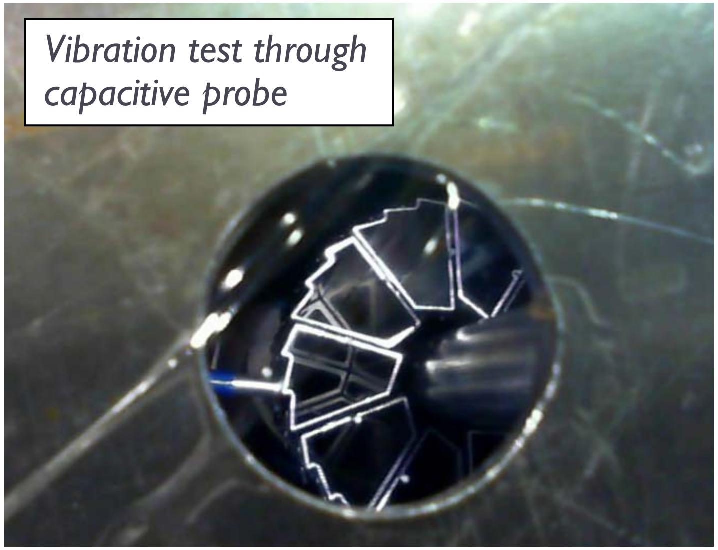
PXL Position Control



Sector in the metrology setup

- Metrology survey
  - 3D pixel positions on sector are measured with touch probe and related to tooling balls
  - Sector tooling ball positions related to kinematic mounts

  → Detector-half is fully mapped



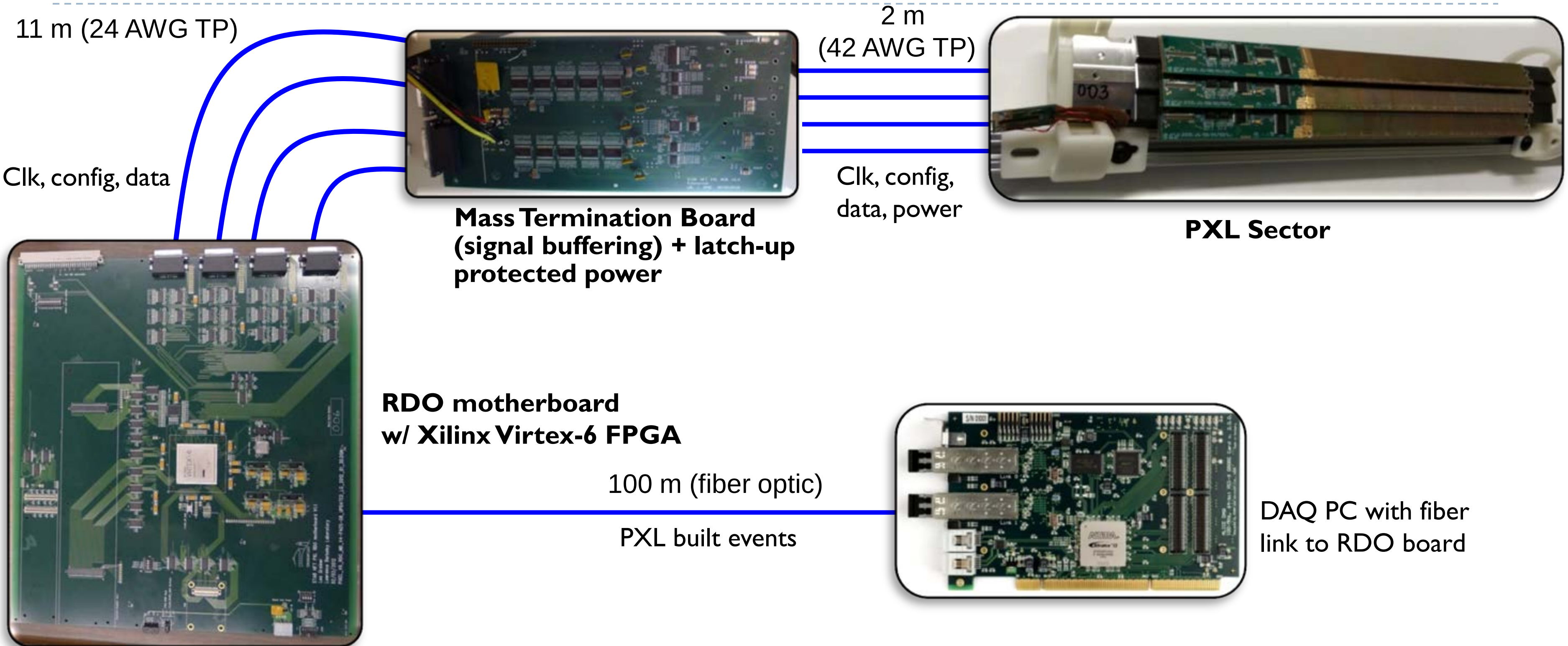
Vibration test through capacitive probe

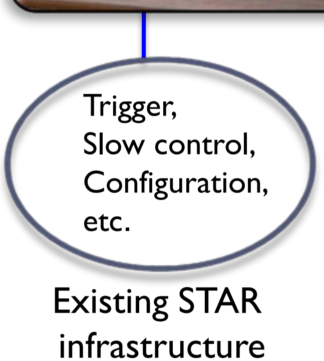
- Position stability
  - Vibration at air cooling full flow: ~5 μm RMS
  - Stable displacement at full air flow: ~30 μm
  - Stable displacement at power on: ~5 μm

  → Global hit position resolution: ~ 6.2 μm

HFT DCA pointing resolution: **(10 ⊕ 24/p) μm**

PXL Detector Powering and Readout Chain

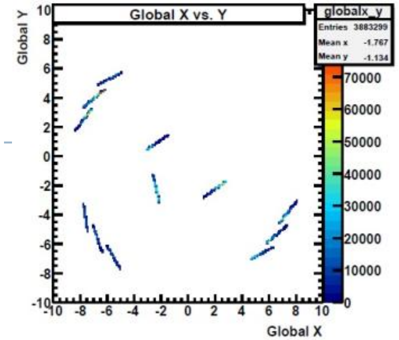




<u>Highly parallel system</u>

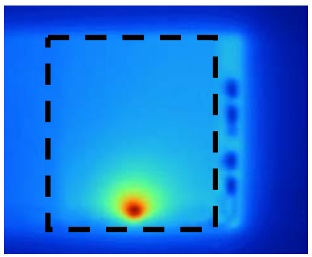
- 4 ladders per sector
- 1 Mass Termination Board (MTB) per sector
- 1 sector per RDO board
- 10 RDO boards in the PXL system

2013 Engineering Run

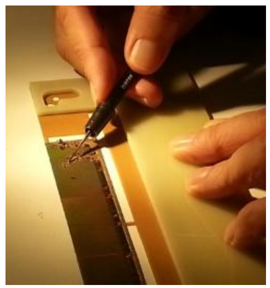


Engineering run geometry

- PXL Engineering Run assembly crucial to deal with a number of unexpected issues



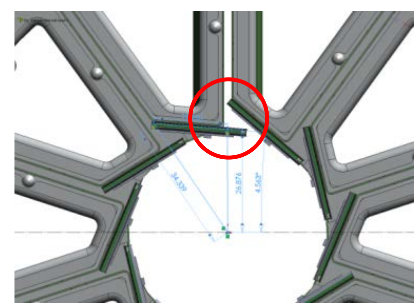
Sensor IR picture



Flawed ladder dissection: searching for shorts

- Shorts between power and gnd, or LVDS outputs
- Adhesive layer extended in both dimensions to increase the portion coming out from underneath the sensors
- Insulating solder mask added to low mass cables

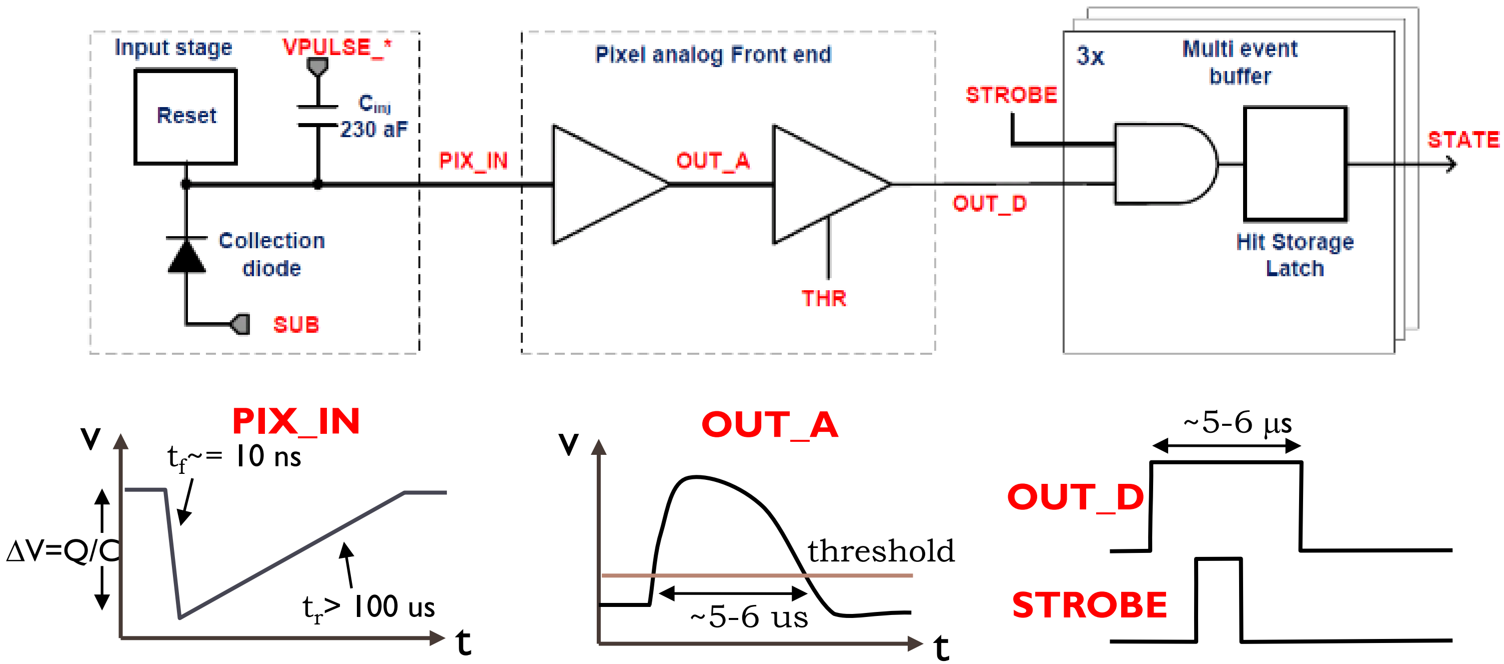
- Mechanical interference in the driver boards on the existing design.
- The sector tube and inner ladder driver board have been redesigned to give a reasonable clearance fit
- Inner layer design modification: ~ 2.8 cm inner radius



Inner layer design

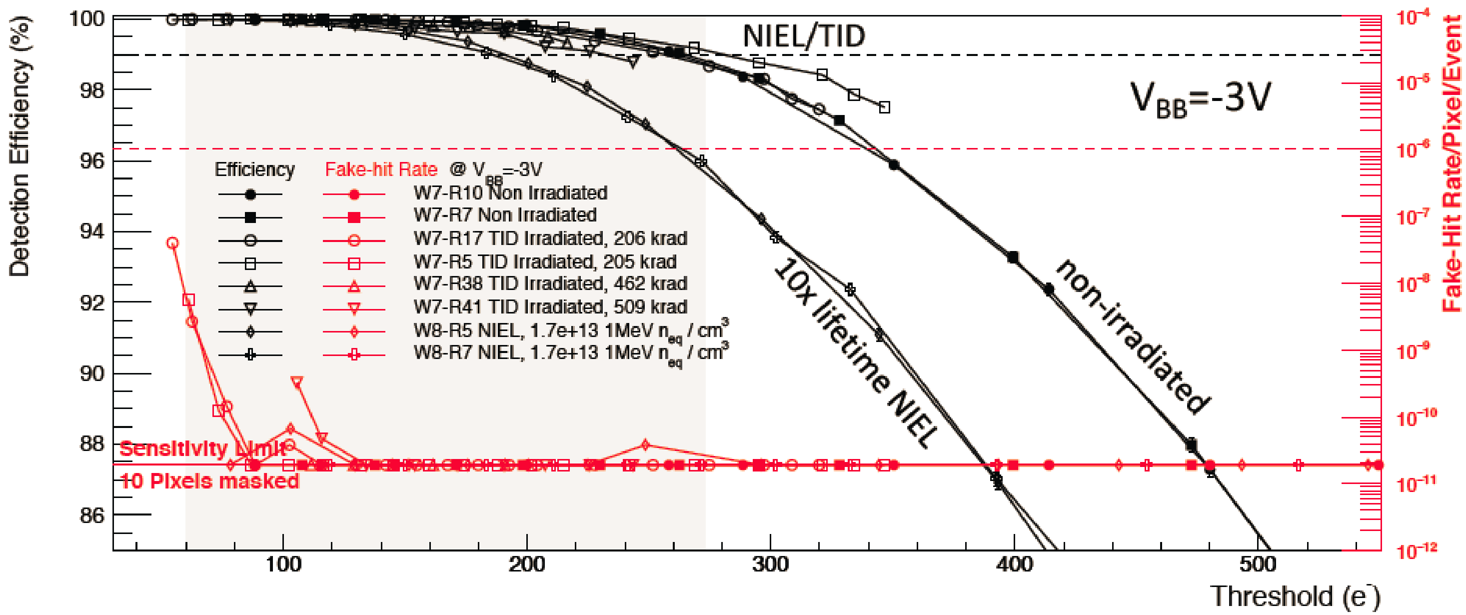
- Limited capability to remotely control power and current limits
- After the engineering run added functionality to the Mass Termination Board:
  - remote setting of LU threshold and ladder power supply voltage + current and voltage monitoring

ALPIDE Pixel Architecture



ALPIDE performance

Detection Efficiency and Fake-Hit Rate



- Big operational margin with only 10 masked pixels (0.002%)
- Chip-to-chip fluctuations negligible
- Non-irradiated and NIEL/TID chips show similar performance
- Sufficient operational margin after 10x lifetime NIEL dose

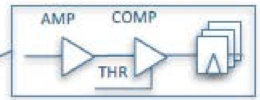
From ITS Upgrade Talk @ QuarkMatter17, February '17

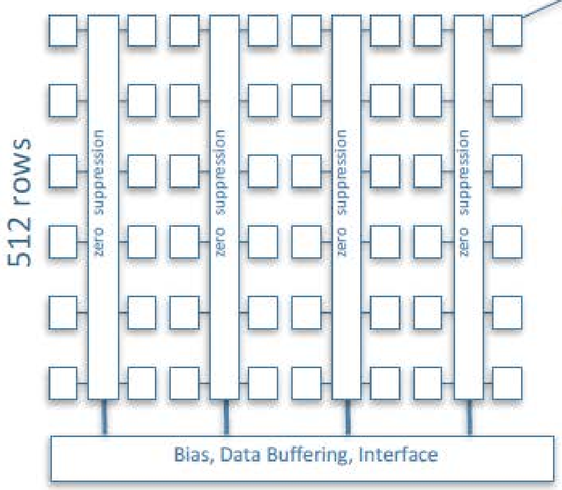
ALPIDE Architecture

→ see also R.Tieulent on the ALICE MFT (this workshop)

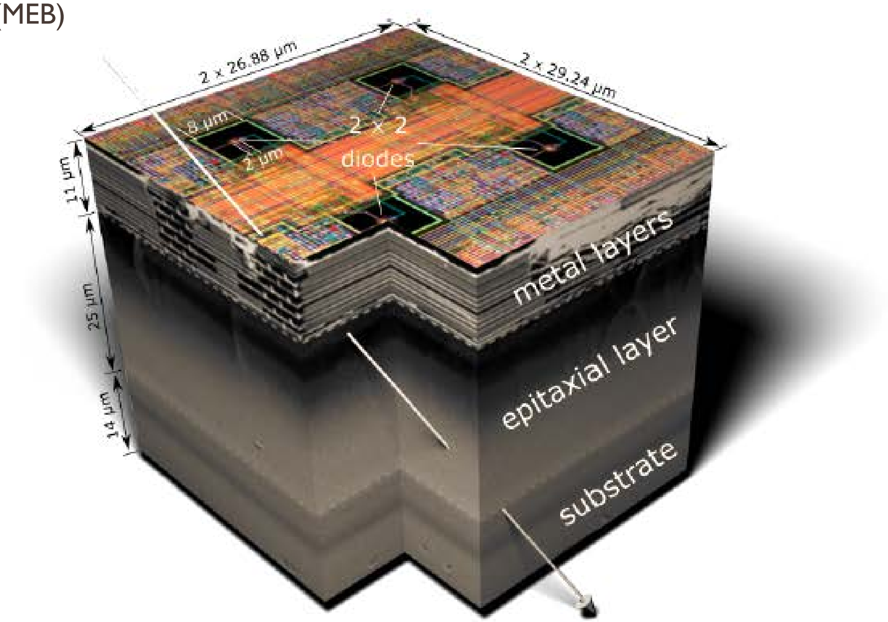
Priority Encoder (AE-RD)
1024 pixel columns
(32 regions x 16 double-columns)

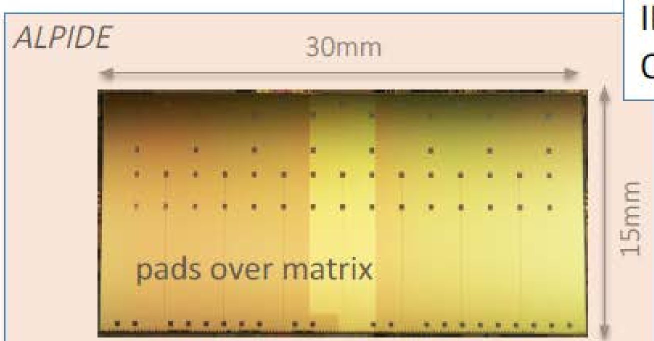
In pixel:
- Amplification
- Discrimination
- 3 hit storage registers (MEB)





external trigger
or
Continuous



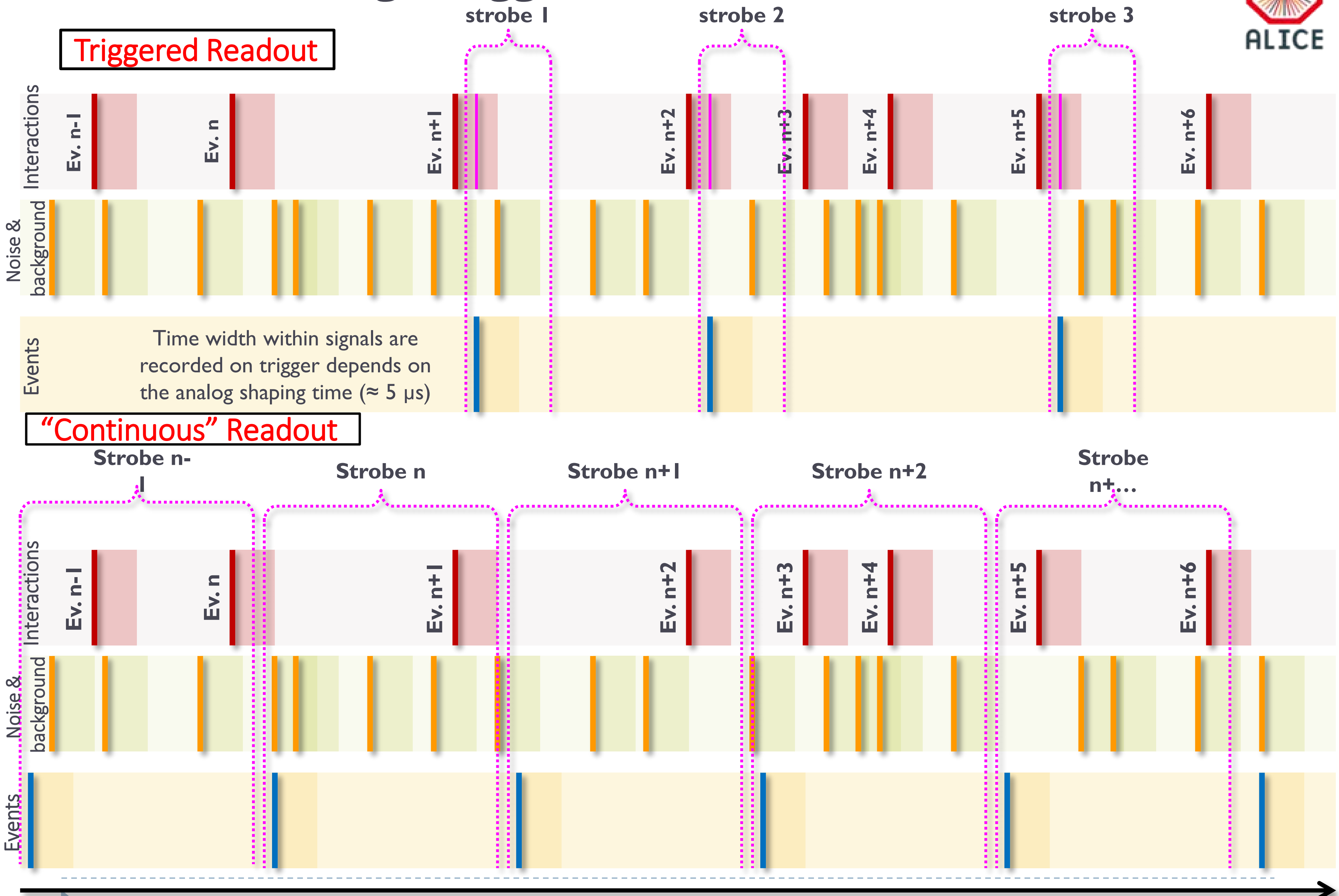


IB: 50µm thick
OB: 100µm thick

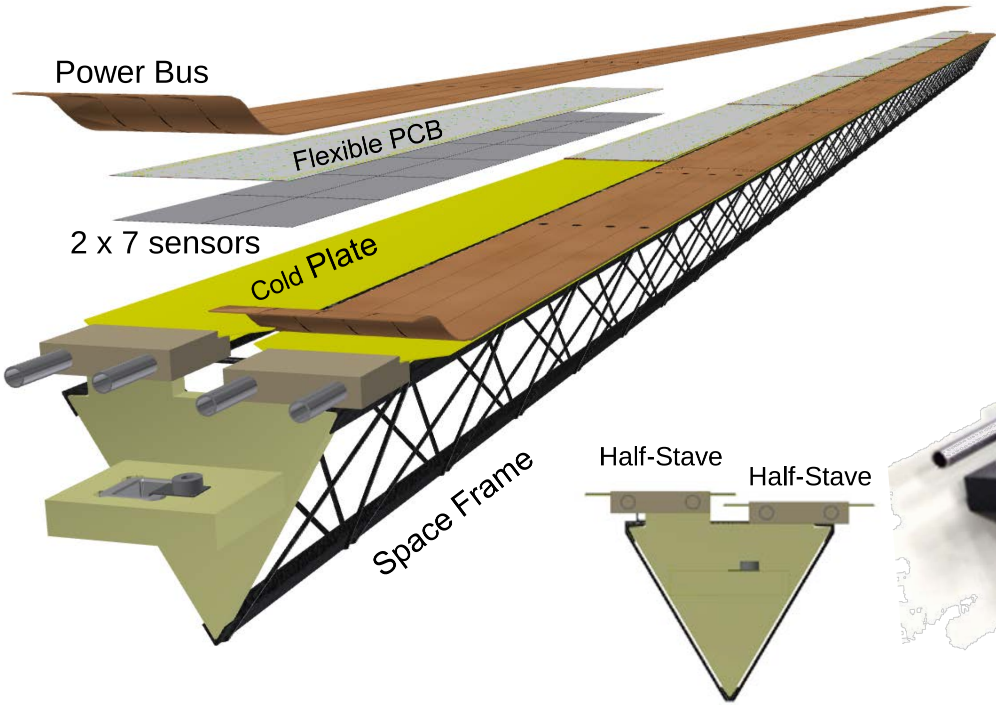
Power: 40 mW/cm^2
Trigger rate: 100 kHz
Integration time: < 20 µs
Read out up to 1.2 Gbit/s.

130,000 pixels / cm^2 27x29x25 µm^3
spatial resolution: ~ 5 µm (3-D)
Max particle rate: 100 MHz / cm^2
fake-hit rate: ~ 10^{-10} pixel / event
power : ~ 300 nW /pixel

ALPIDE Timing: Triggered & "Continuous" Readout



ITS Outer Barrel



Outer Barrel (OB)

<radius> (mm): 194, 247, 353, 405

Nr. staves: 24, 30, 42, 48

Nr. Chips/layer: 6048 (ML), 17740(OL)

Power density < 100 mW / cm^2

Length (mm): 900 (ML), 1500 (OL)

Nr. modules/stave: 4 (ML), 7 (OL)

Material thickness: ~ 1% X_0

Throughput (@100kHz): < 3Mb/s × cm^{-2}