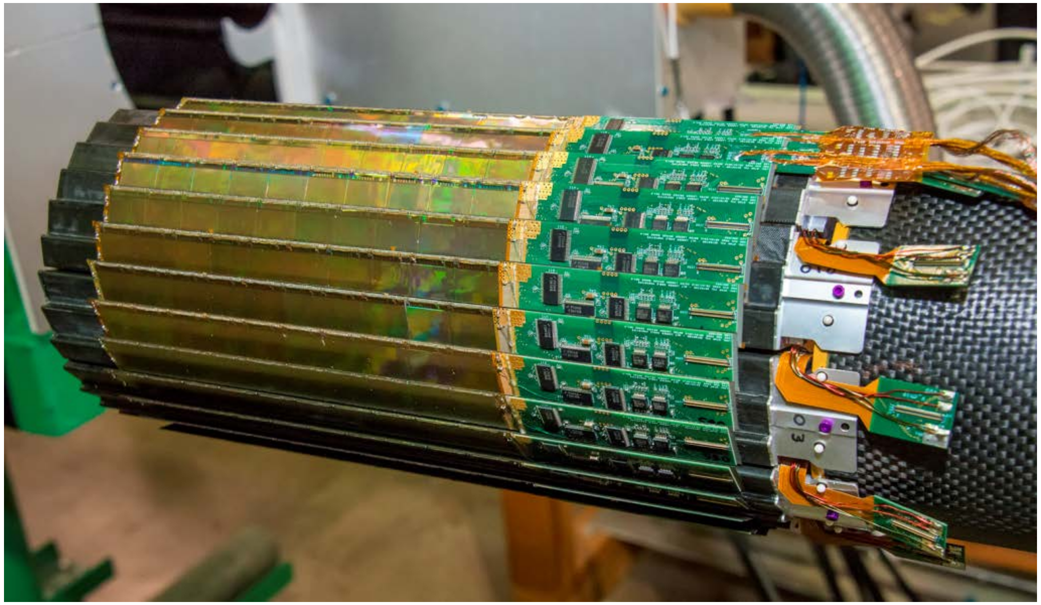
The STAR Pixel detector



Giacomo Contin *for the STAR Collaboration*

Lawrence Berkeley National Laboratory

PIXEL 2016 - 8th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging

Sestri Levante, 5-9 September 2016

G. Contin | *gcontin@lbl.gov*

Lawrence Berkeley National Laboratory

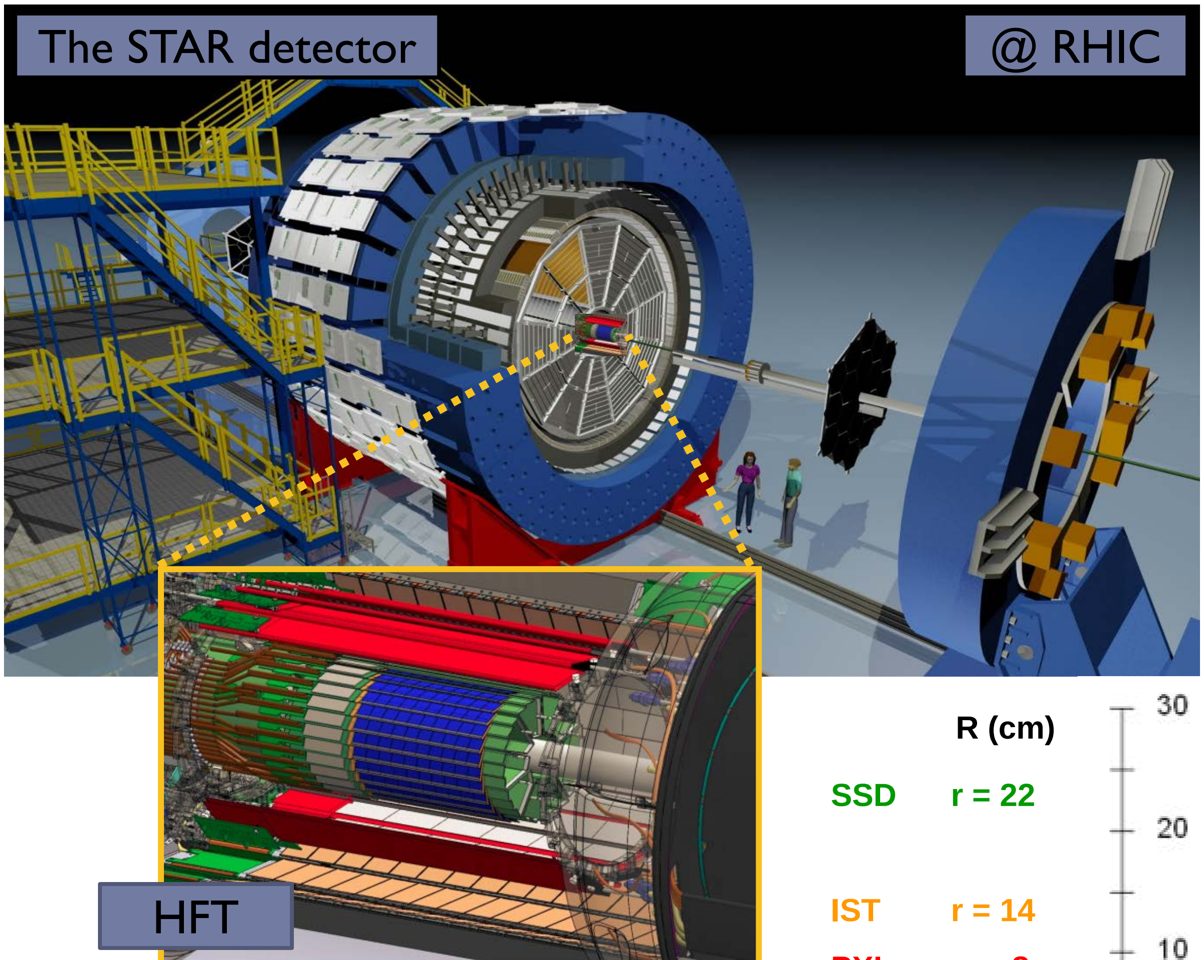
Outline

- A MAPS-based detector
- Construction
- Operations, Performance, Lessons Learned
- Conclusions

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

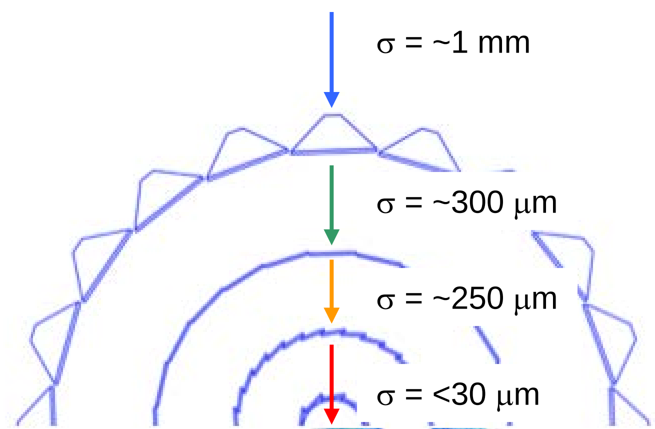
TPC – Time Projection Chamber (main tracking detector in STAR)

HFT – Heavy Flavor Tracker

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

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

Tracking inwards with gradually improved resolution:



The PiXeL detector (PXL)

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

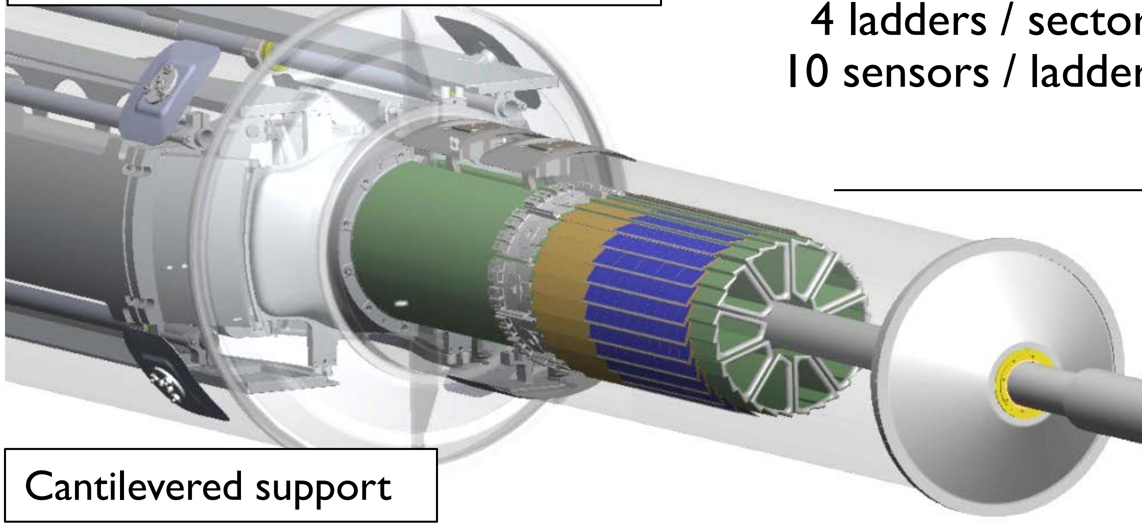
PXL Design Parameters

DCA Pointing resolution	(10 ⊕ 24 GeV/p·c) μm
Layers	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)
Material budget first layer	X/X_0 = 0.39% (Al conductor cable)
Number of pixels	356 M
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

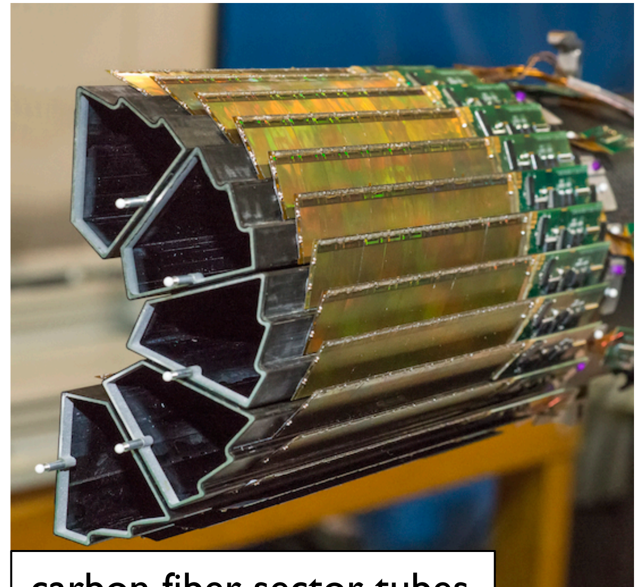
Mechanical support with kinematic mounts (insertion side)



Cantilevered support

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

Highly parallel system



carbon fiber sector tubes

Material budget on the inner layer

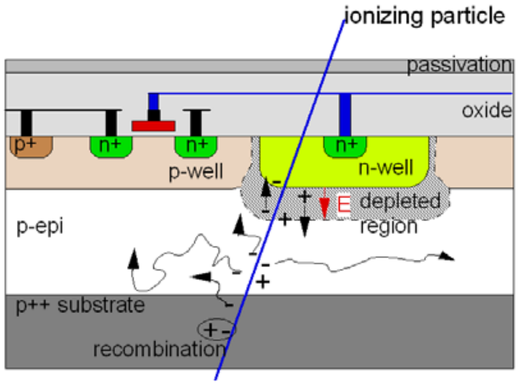
- Thinned sensor: 50 μm - 0.068% X_0
- Aluminum-conductor cable (32 μm-thick traces) - 0.128% X_0
- Carbon fiber stiffener (125 μm) and sector tube (250 μm) - 0.193% X_0
- Air cooled

0.388% X_0

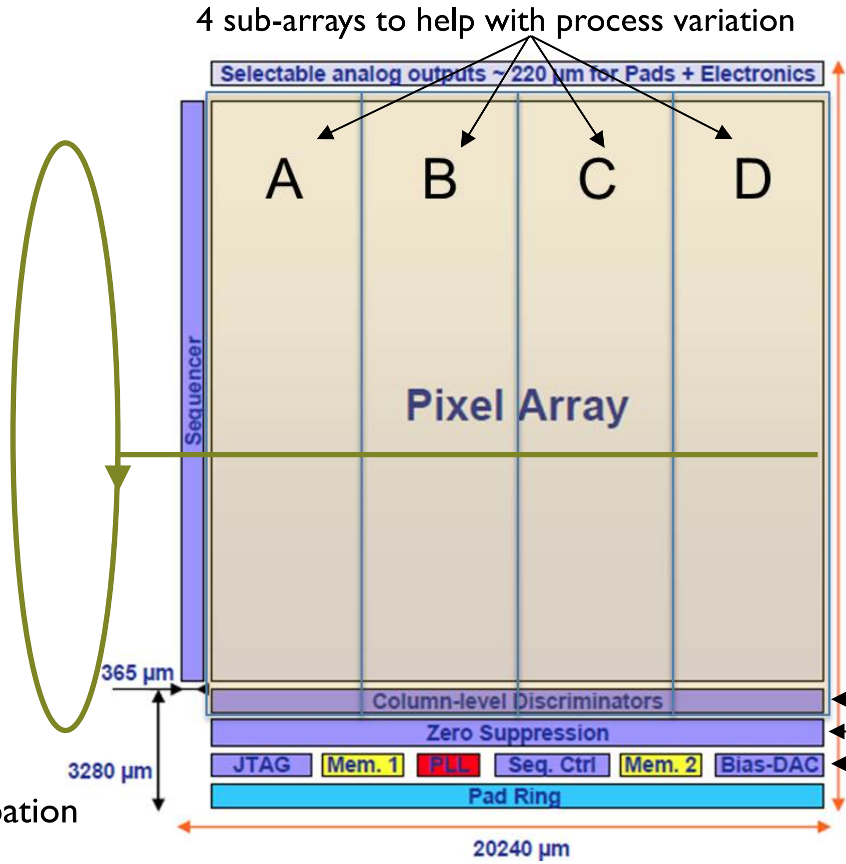
Ladder with 10 MAPS sensors (~ 2×2 cm each)

PXL *MAPS* sensor

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

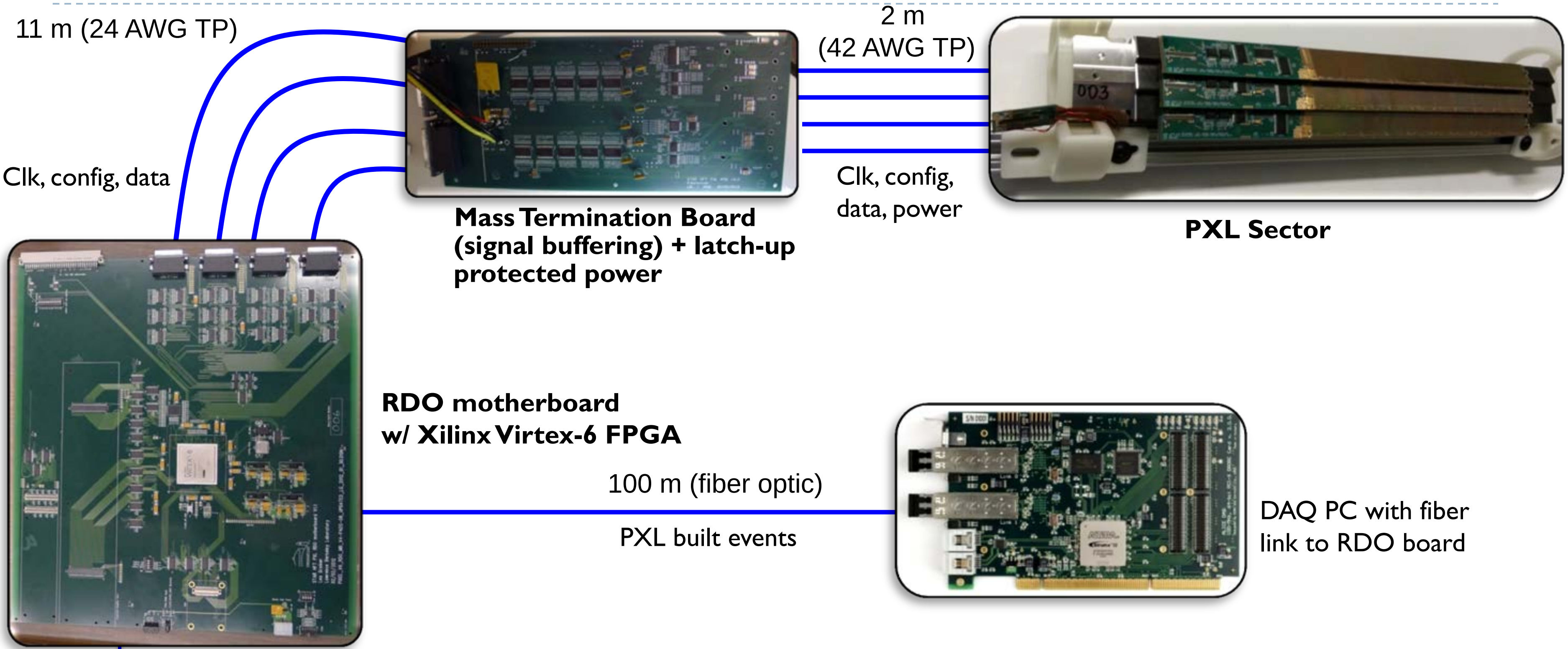


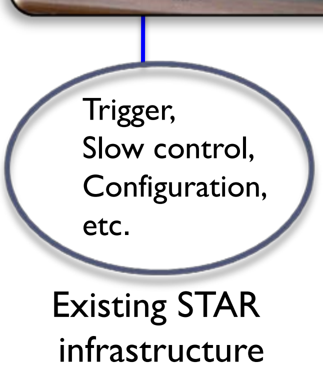
- High resistivity p-epi layer
  - Reduced charge collection time
  - Improved radiation hardness
- S/N ~ 30
- MIP Signal ~ 1000 e-
- **Rolling-shutter readout**
  - A row is selected
  - For each column, a pixel is connected to discriminator
  - Discriminator detects possible hit
  - Move to next row
- 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

PXL Detector Powering and Readout Chain



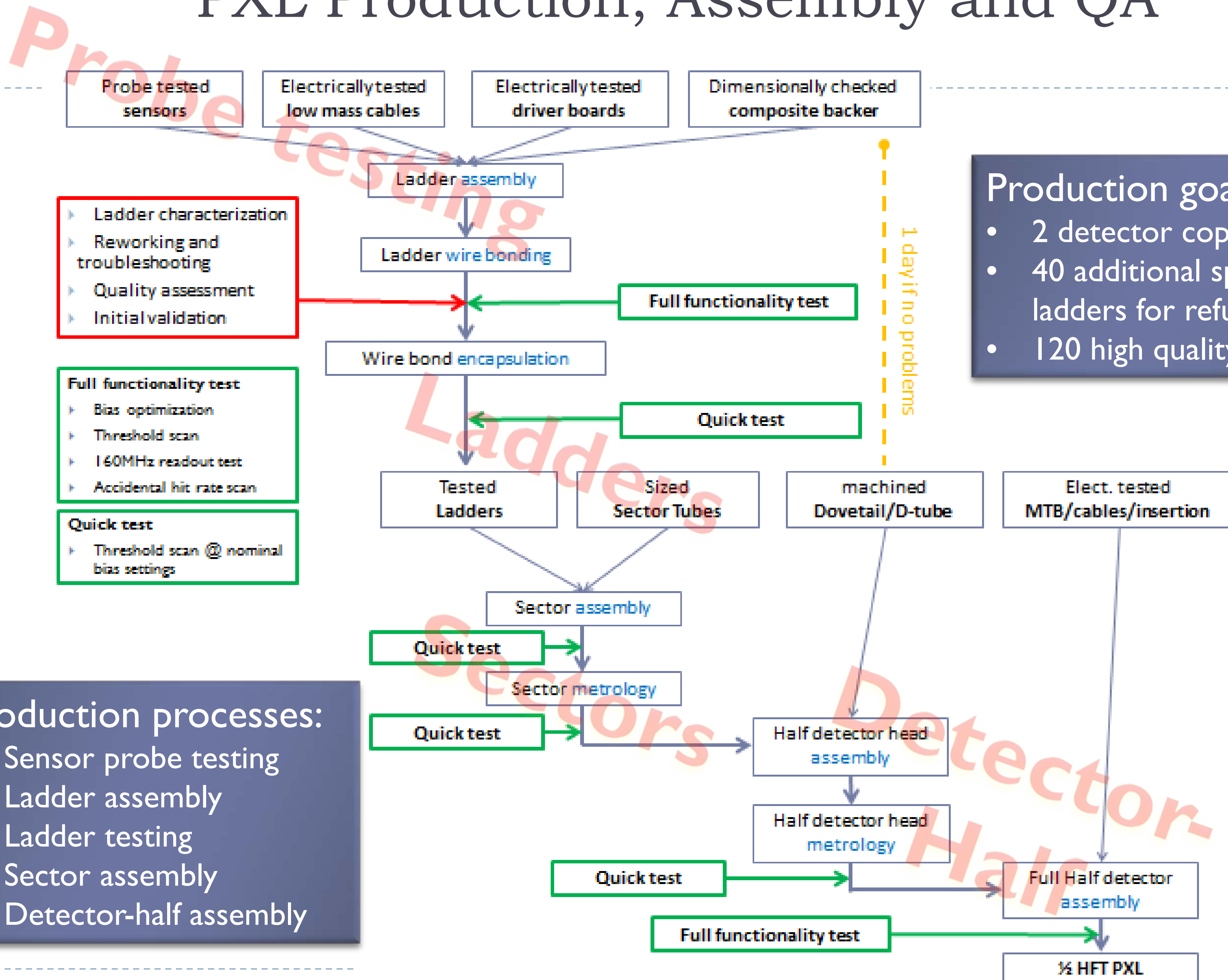


Highly parallel system

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

- Construction

PXL Production, Assembly and QA



Production goals:

- 2 detector copies
- 40 additional spare ladders for refurbishment
- 120 high quality ladders

Production processes:

- Sensor probe testing
- Ladder assembly
- Ladder testing
- Sector assembly
- Detector-half assembly

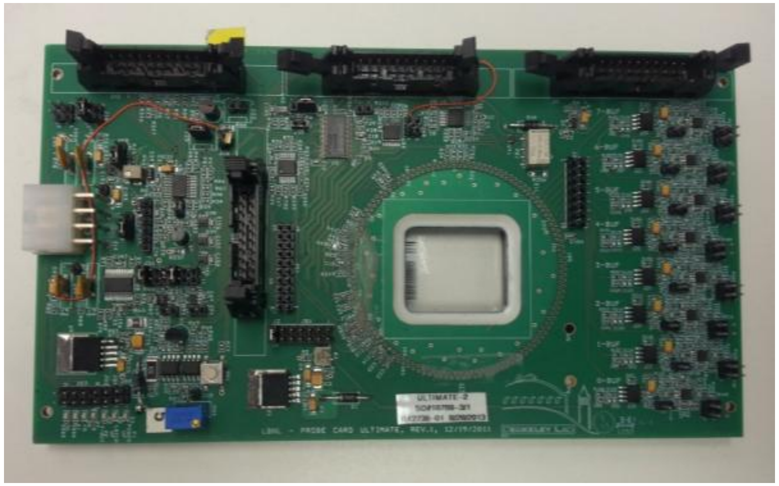
PXL Probe Testing

- **Thinned and diced 50 μm-thick sensors**
- **Full sensor characterization**
- **Full speed readout (160 MHz)**

- **Custom made vacuum chuck**
- Testing up to 18 sensors per batch (optimized for sensor handling in 9-sensor carrier boxes)
- Manual alignment (~1 hr)
- LabWindows GUI for system control
- Automated interface to a database

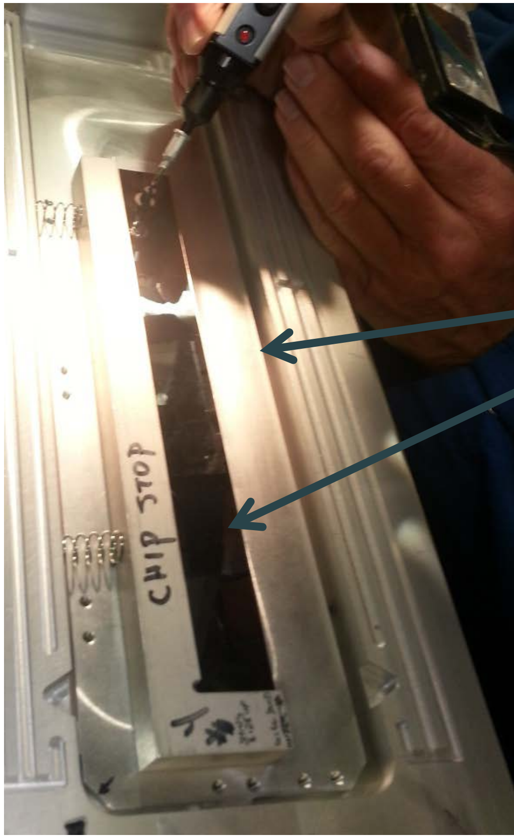
curved thinned sensors

- Sensors built-in testing functionality
- **Proper probe pin design for curved thinned sensors**
- Yield 46% - 60% (spare probe cards)
- Administrative control of sensor ID



Probe card with readout electronics

Ladder Assembly



Sensor positioning

Precision vacuum chuck fixtures to **position sensors by hand**

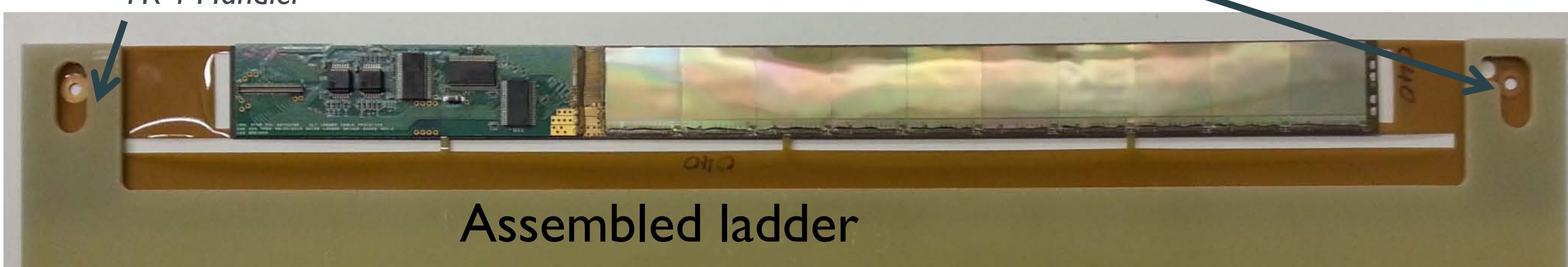
Sensors are positioned **with butted edges.** Acrylic adhesive prevents CTE difference based damage.

Weights taken at all assembly steps to track material and as QA.

Hybrid cable with carbon fiber stiffener plate on back in position to glue on sensors.

Cable reference holes for assembly

FR-4 Handler



Assembled ladder

From ladders to sectors… to detector halves

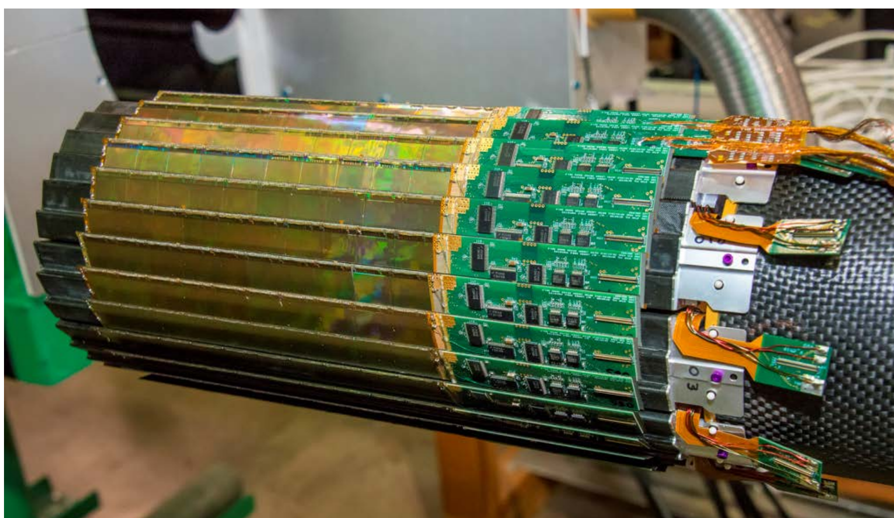
Sectors

- Ladders are glued on carbon fiber sector tubes in 4 steps
- Pixel positions are measured and related to tooling balls
- After touch probe measurements, sectors are tested electrically for damage from metrology

Sector assembly fixture

Sector in the metrology setup

A detector half

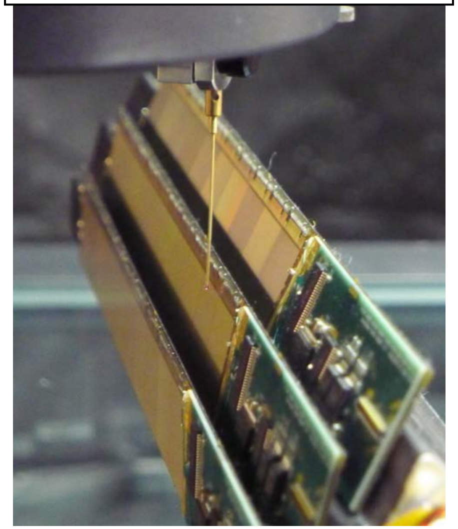


Detector half

- Sectors are mounted in dovetail slots on detector half
- Metrology is done to relate sector tooling balls to each other and to kinematic mounts

PXL Position Control

Sector in the metrology setup



- Metrology survey
  - 3D pixel positions on sector (within ~10 μm) are measured with touch probe and related to tooling balls
  - Sector tooling ball positions related to kinematic mounts to relate pixel positions to final PXL location

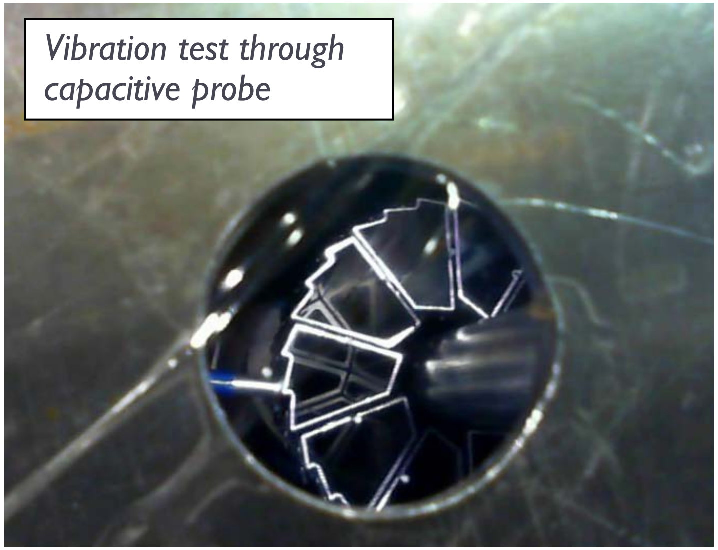
→ Detector-half is fully mapped

- 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

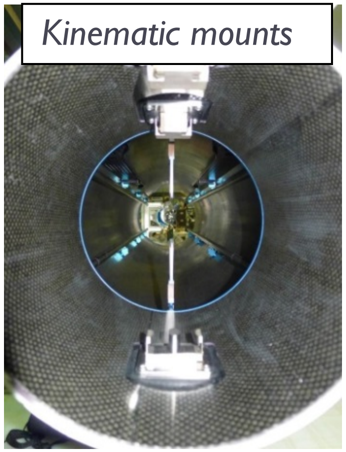
→ Global hit position resolution: ~ 6.2 μm

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

Vibration test through capacitive probe

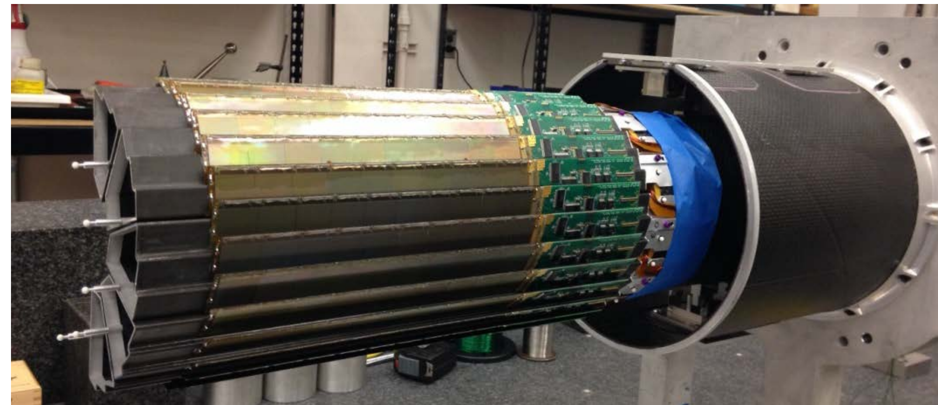


PXL Installation in STAR

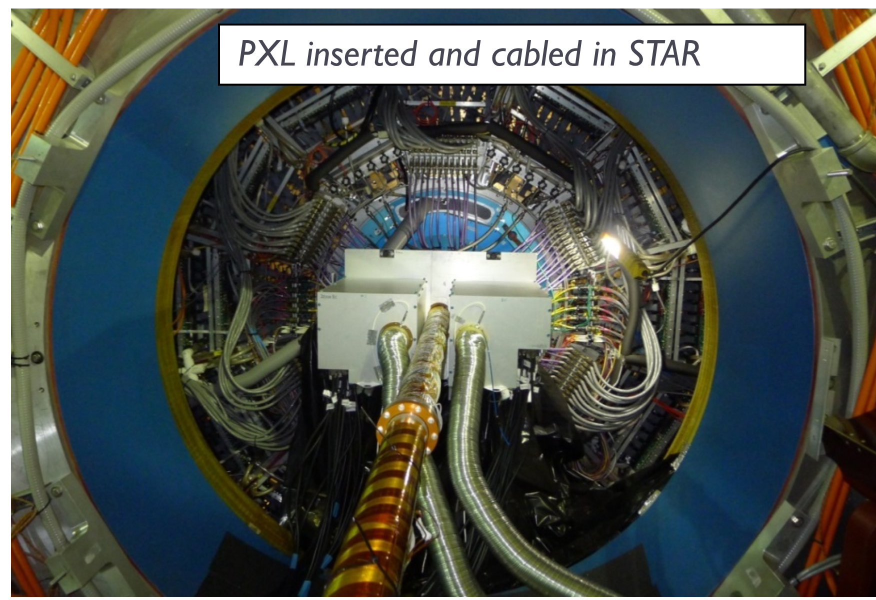

Kinematic mounts

Novel insertion approach

- Inserted along rails and locked into a kinematic mount inside the support structure
- It can be replaced in < 1 day with a spare copy


duplicate, truncated PXL support tube with kinematic mounts


Insertion in STAR

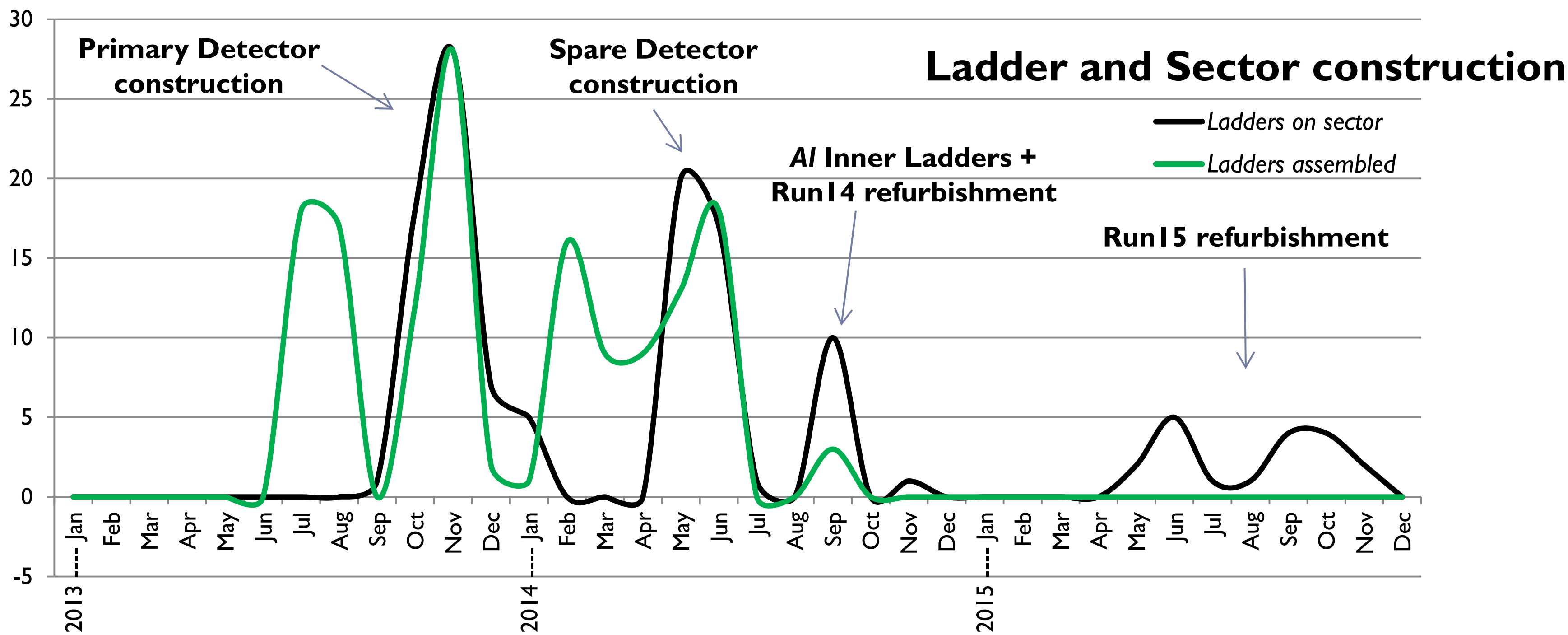

PXL inserted and cabled in STAR

PXL production timeline

- Delivered:
  - **2014 Run:** Primary Detector, 2 *aluminum cable* inner ladders, others in *copper*
  - **2015-2016 Runs:** 2 detector copies, all inner ladders in *aluminum*

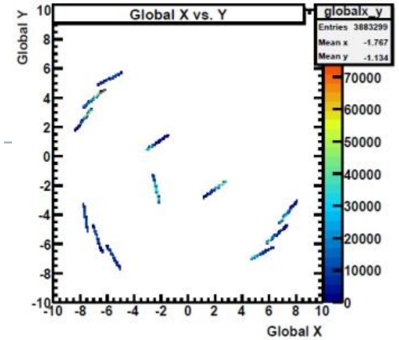
- Sector refurbishment:
  - After each STAR Run for *latch-up* induced damage
  - After power supply accident during 2015 Run installation

Overall stats	#
Assembled ladders	146
Installed on sectors	127
Ladder tests	~2000



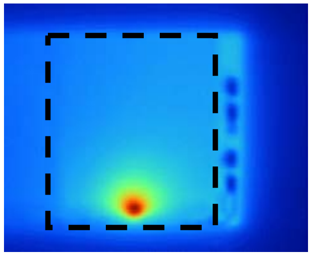
- Operations, Performance, Lessons Learned

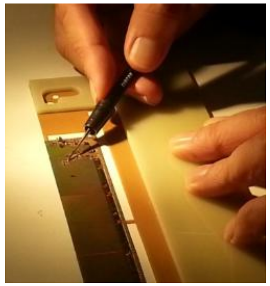
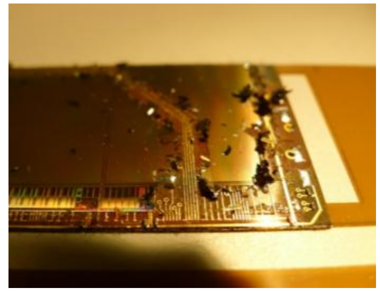
2013 Engineering Run



Engineering run geometry

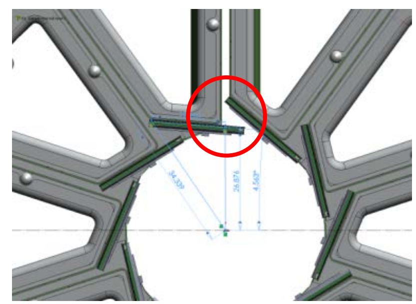
- PXL Engineering Run assembly crucial to deal with a number of unexpected issues


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

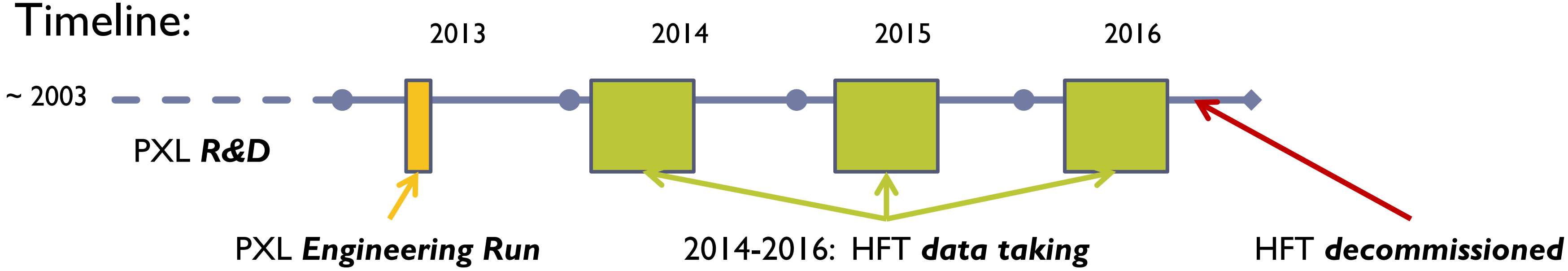
- Mechanical interference in the driver boards on the existing design.
- The sector tube and inner ladder driver board have been redesigned to give a reasonable clearance fit
- Inner layer design modification: ~ 2.8 cm inner radius


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

PXL data taking

- Timeline:

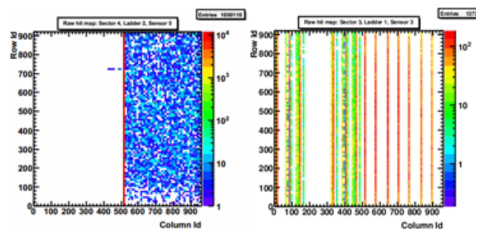


- PXL Operations
  - Hit multiplicity per sensor: up to 1000/inner-sensor, 100/outer-sensor
  - Dead time up to ~6%
  - Typical trigger rate: 0.8-1 kHz
  - Latch-up reset events: 2 latch-up/min
  - Periodic reset to clear SEUs

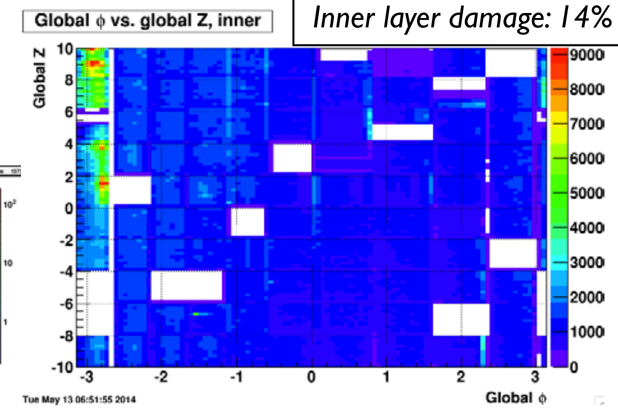
- Collected *minimum bias* events in the PXL acceptance:
  - 2014 Run: ~ 1.2 Billion Au+Au @ $\sqrt{s_{NN}}$ = 200GeV
  - 2015 Run: { ~ 1 Billion p+p; ~ 0.6 Billion p+Au } @ $\sqrt{s_{NN}}$ = 200GeV
  - 2016 Run: { ~ 2 Billion Au+Au; ~ 0.3 Billion d+Au } @ $\sqrt{s_{NN}}$ = 200GeV

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%

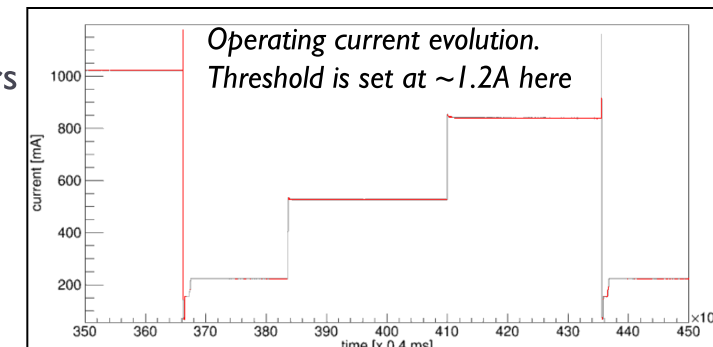


- Latch-up tests at *BASE facility* (LBL) to measure latch-up cross-section and reproduce damage
  - 50 μm & 700 μm thick, low and high resistivity sensors; PXL ladders
  - Irradiation with heavy-ions and protons

Latch-up phenomenon:

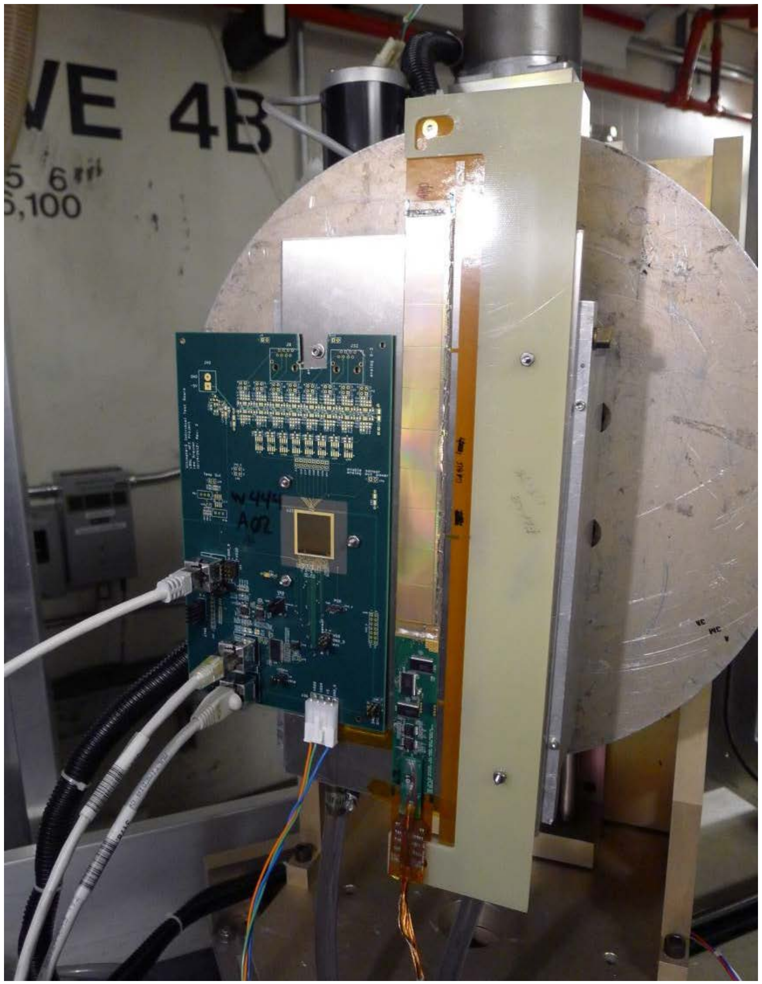
- Self feeding short circuit caused by single event upset
- Can only be stopped by removing the power

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

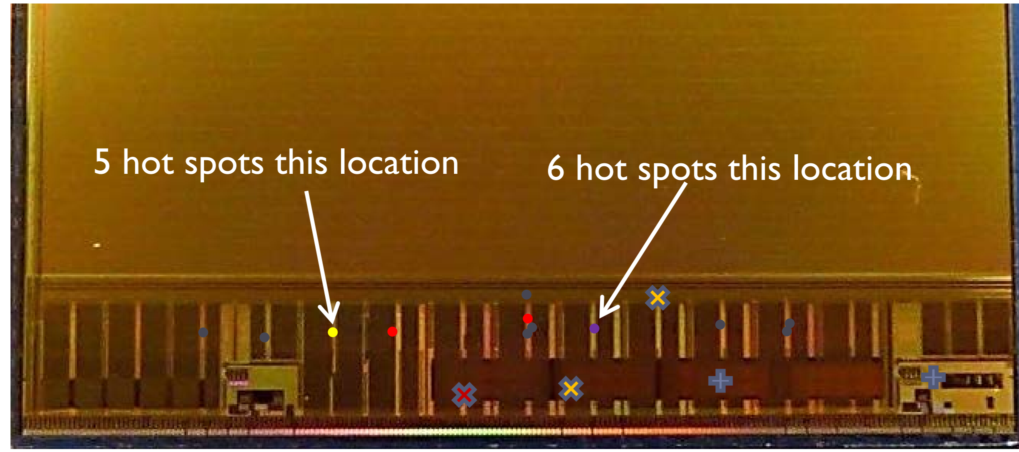


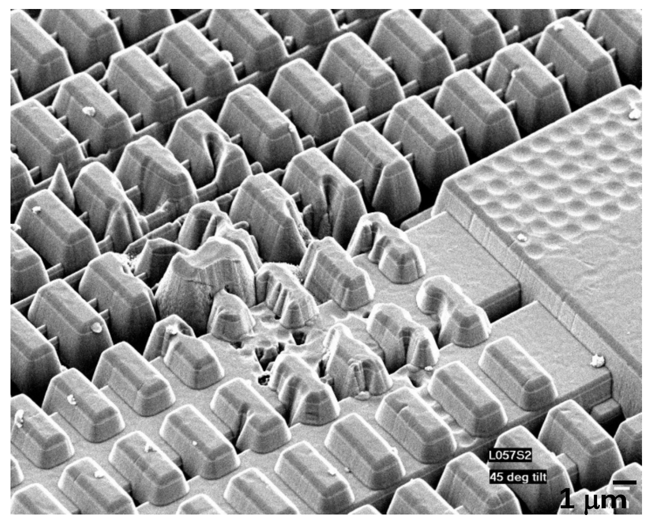
Latch-up test setup and damage analysis

Individual sensor test boards and ladders mounted on cooling plate



IR "hotspots" locating the damage tend to favor particular structures (isolated buffers with specific structure pitch)





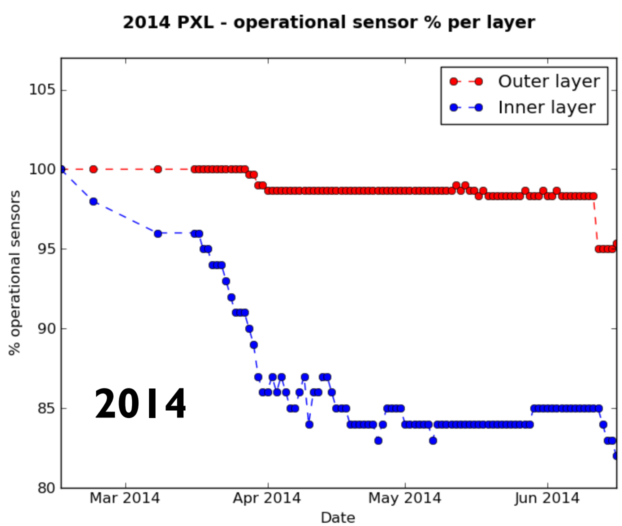
Pixel sensor layers deconstructed (plasma etching technique) and viewed with SEM.

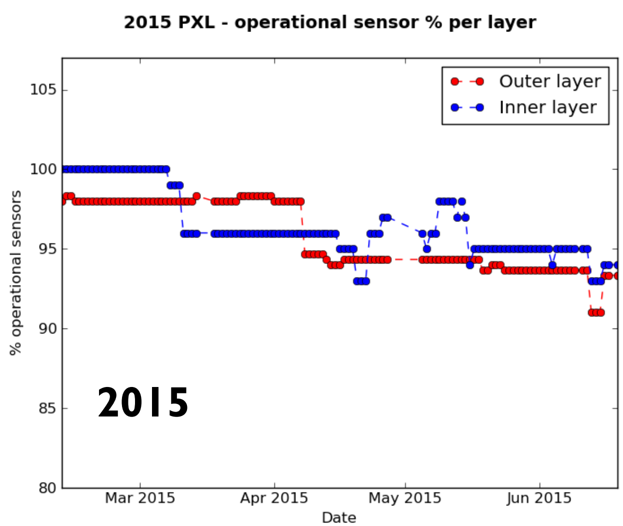
The layers appear to be melted

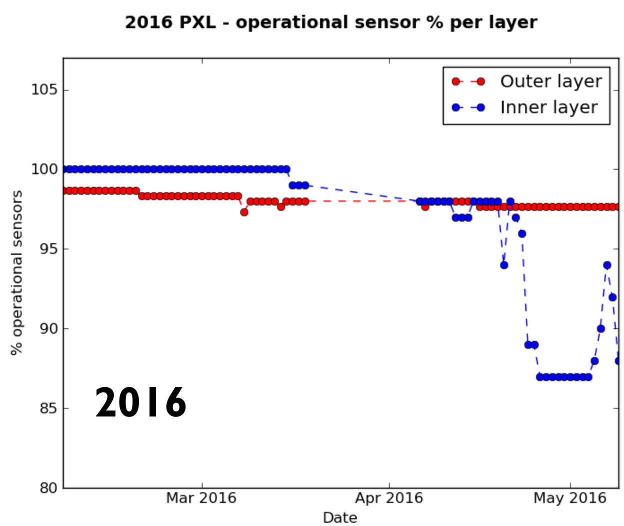
Damage evolution

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

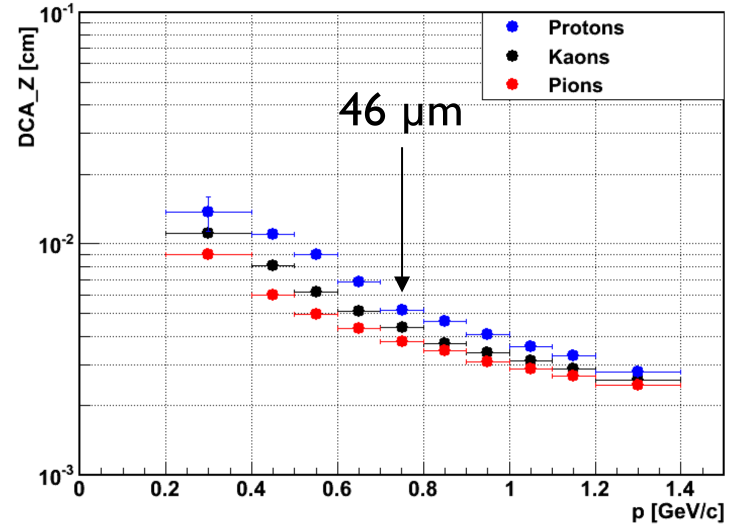




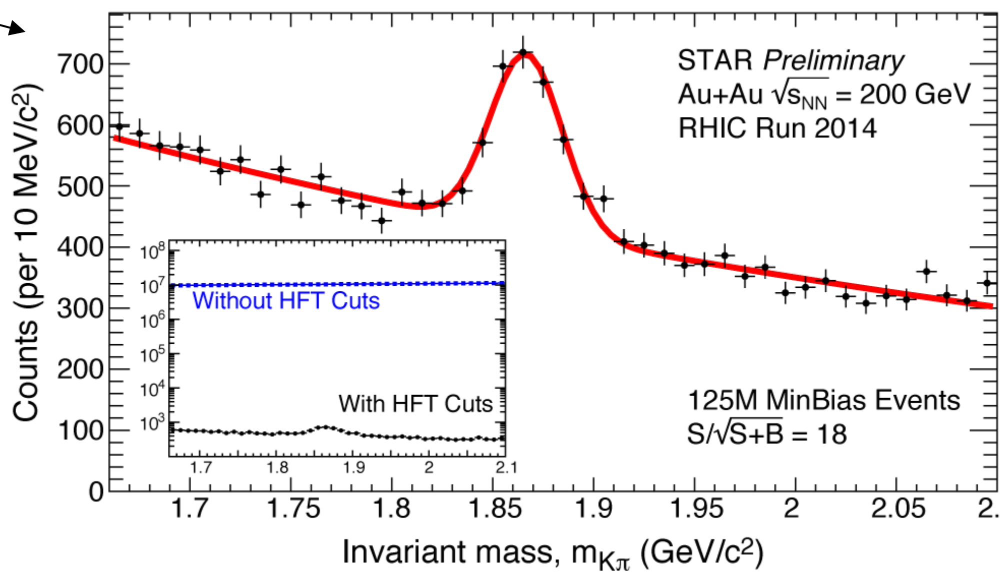


HFT Performance from 2014 data

- DCA pointing resolution
  - Design requirement exceeded: 46 μm for 750 MeV/c Kaons for the **2 sectors** equipped **with aluminum cables on inner layer**
  - ~ 30 μm for p > 1 GeV/c
  - From 2015: all sectors equipped with aluminum cables on the inner layer



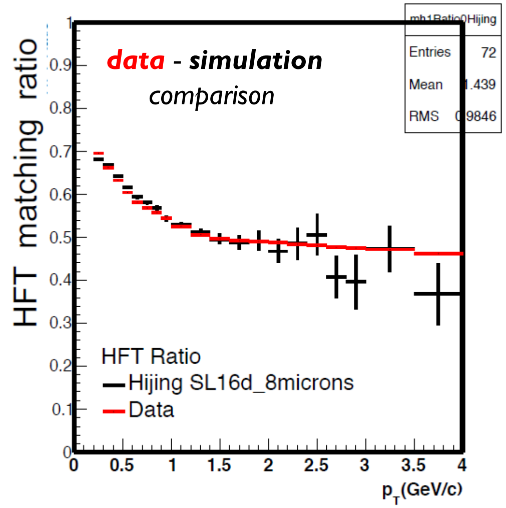
***$D^0 \rightarrow K\ \pi$ production** in $\sqrt{s_{NN}}$ = 200GeV Au+Au collisions (First reconstruction of a small subsample)*

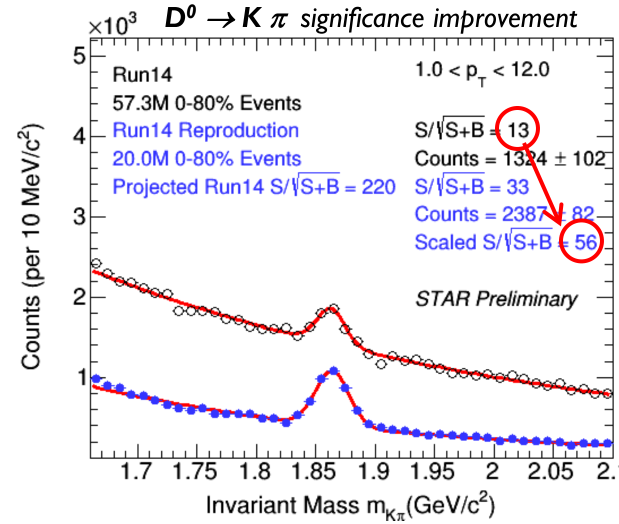


- Physics of D-meson productions
  - High significance signal
  - Nuclear modification factor R_{AA}
  - Collective flow v_2

Software/Firmware issues

- Event decoder issue in 2014 data reconstruction
  - A bug in the PXL hit decoding 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 performance, which now matches the simulation





- Readout firmware issue - 2015 efficiency loss
  - A subtle bug introduced by a change in the PXL RDO firmware led to an efficiency loss in the 2015 Run data
  - The extensive tests with pattern data and the performance of full detector calibrations were inadequate to find this problem
  - A fast-offline tracking QA was put in place only after the 2015 Run
  - A post-run investigation based on external sensor illumination with LED allowed for firmware debugging and correction

Conclusions

- The first generation MAPS-based detector at a collider experiment successfully completed the 3-year physics program at RHIC
- As part of the Heavy Flavor Tracker, the PXL detector enabled STAR to perform a direct topological reconstruction of the charmed hadrons
- The 2013 Engineering Run was crucial for dealing with the unexpected problems that developed during the following physics data taking
- Due to beam-induced damage, the PXL construction phase continued throughout the entire detector life for yearly refurbishment and optimization
- The relatively short duration of the HFT program is not optimal to exploit such a complex detector system, nevertheless the project was successfully completed

Thank you for your attention!