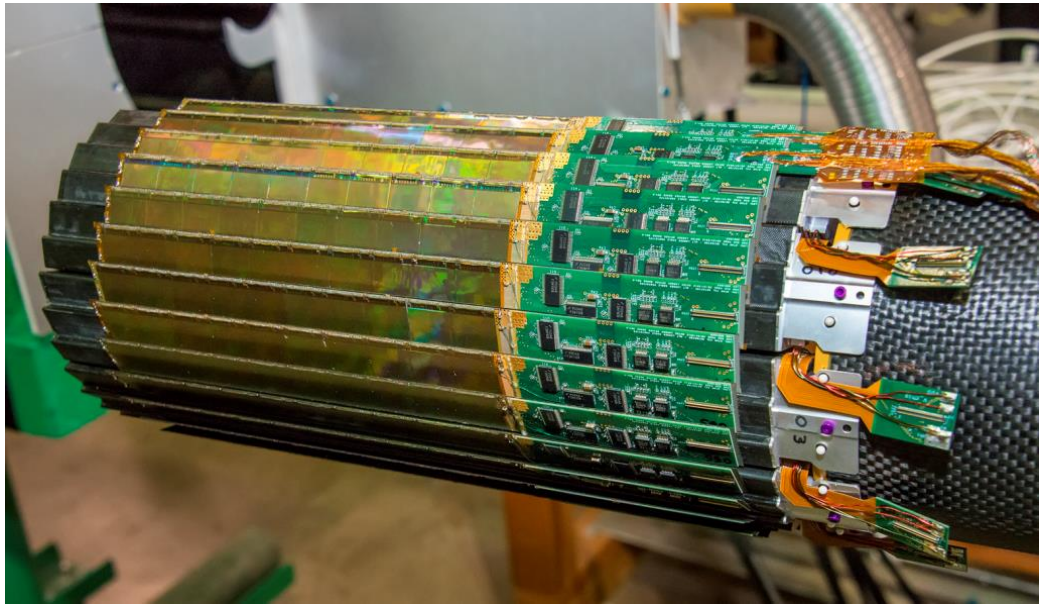
STAR

# Operational Experience of the STAR MAPS Vertex Detector



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BERKELEY LAB

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Lawrence Berkeley National Laboratory

Office of Science

U.S. DEPARTMENT OF ENERGY

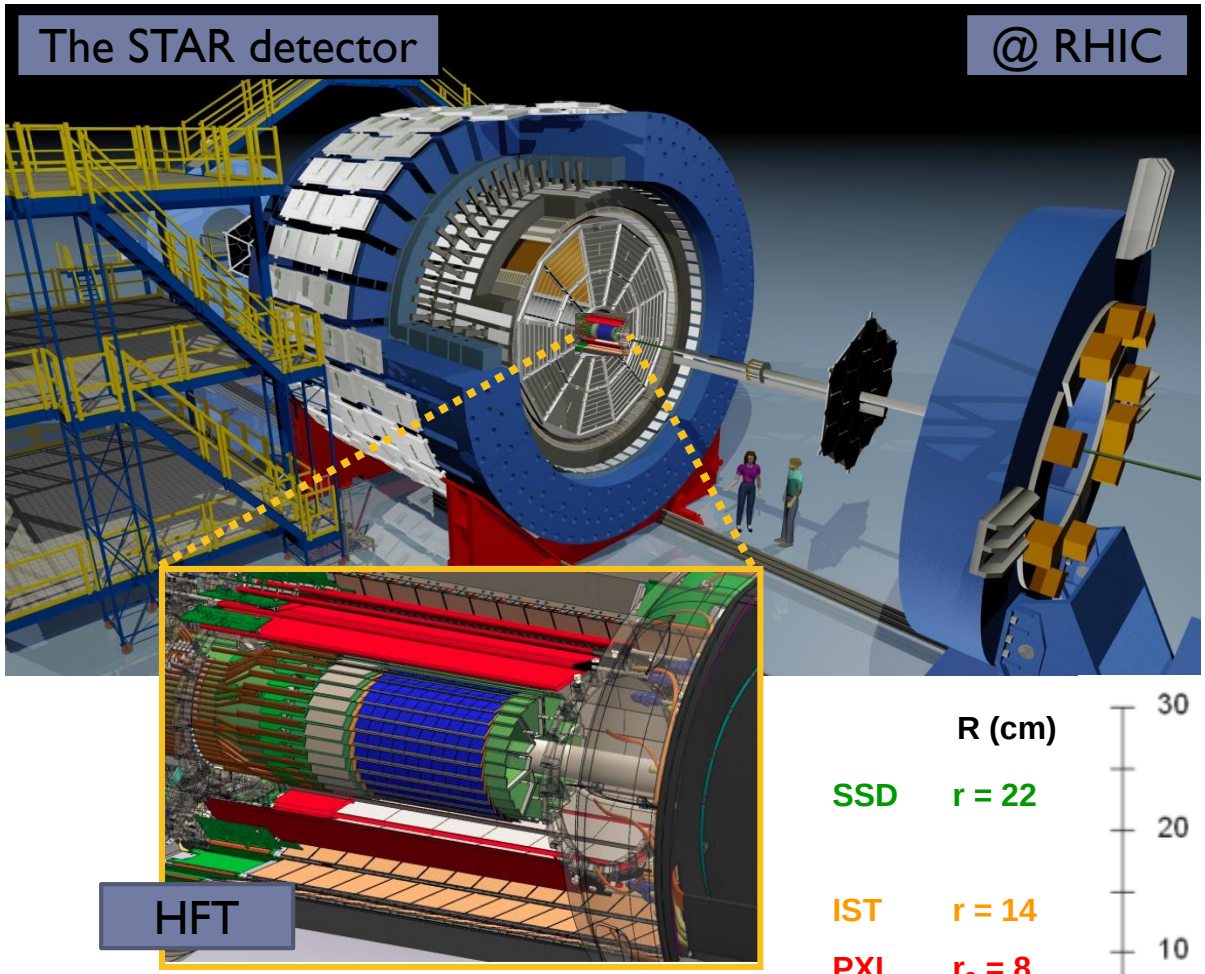
# Outline

- 1st generation MAPS-based vertex detector
  - Detector Design
  - PXL Project Timeline and runs
  - Performance of the HFT
  - Operational aspects and lessons learned
- Conclusions

# The STAR Heavy Flavor Tracker Upgrade

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

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



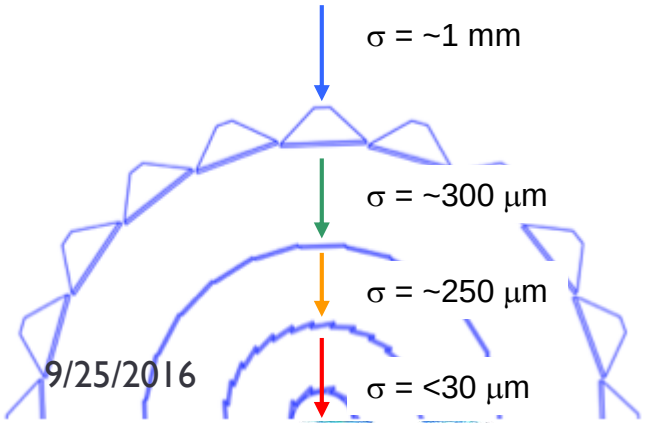

Need to resolve displaced vertices in high multiplicity environment

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

**HFT – Heavy Flavor Tracker**

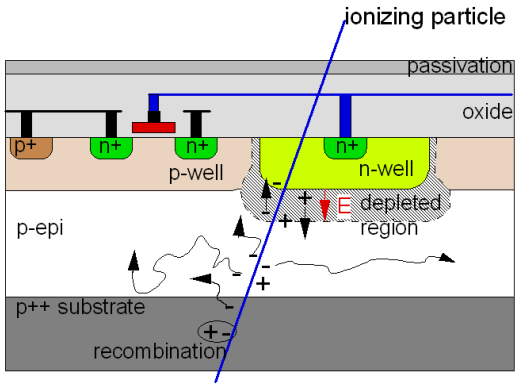
- **SSD – Silicon Strip Detector**
- **IST – Intermediate Silicon Tracker**
- **PXL – Pixel Detector**

Tracking inwards with increasingly improved resolution:

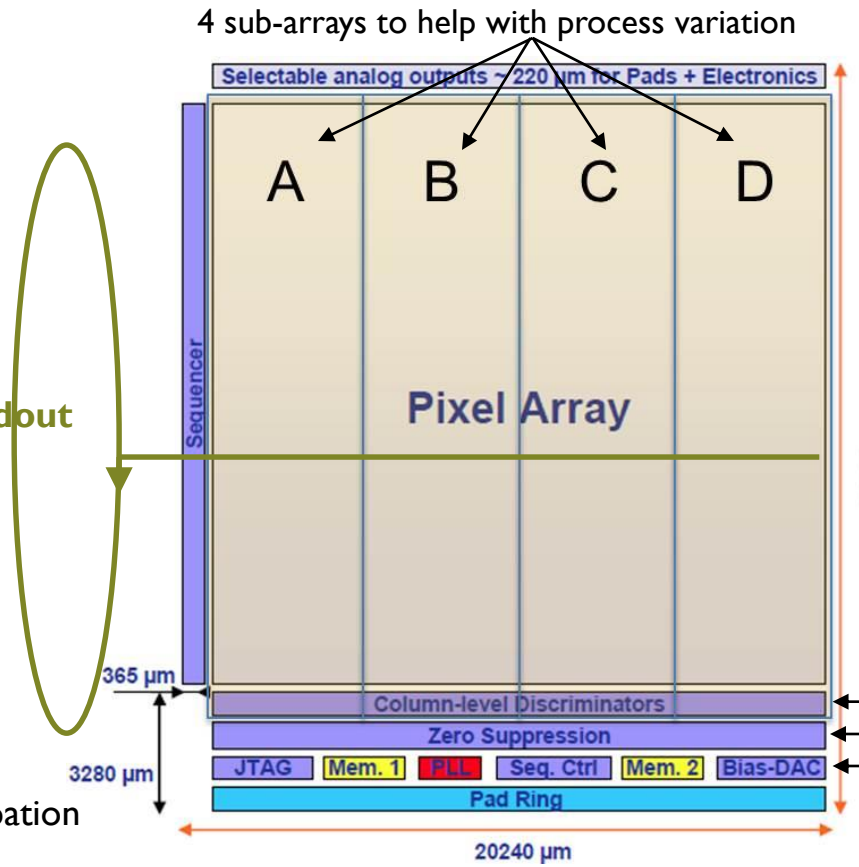


# PXL *MAPS* sensor

- *Ultimate-2:* third revision sensor developed for PXL by the PICSEL group of IPHC, Strasbourg
- AMS OPTO 0.35 process
- Binary readout of hit pixels




- High resistivity p-epi layer
  - Reduced charge collection time
  - Improved radiation hardness
- S/N ~ 30
- MIP Signal ~ 1000 e-
- **Rolling-shutter type 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**
  - 20.7 μm x 20.7 μm pixels
  - 928 rows x 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

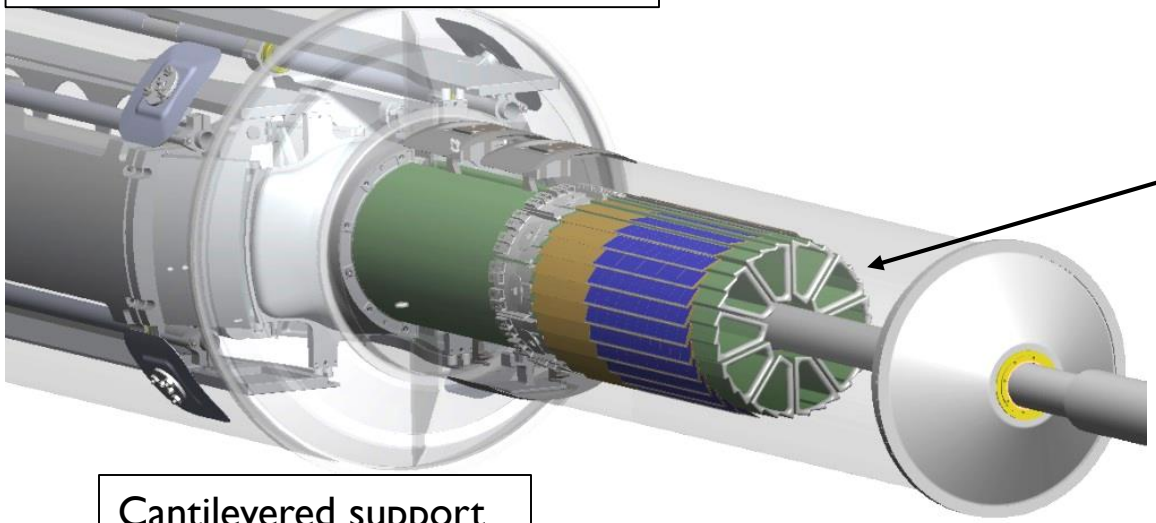
# PXL System Overview

**Basic Detector Element**

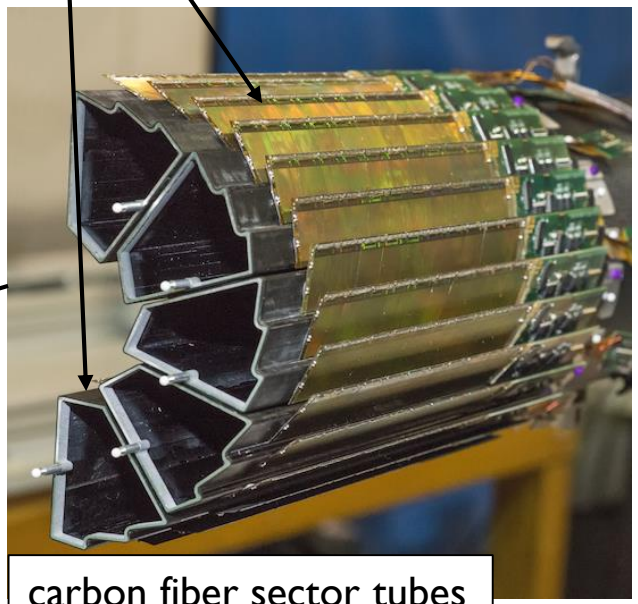
Ladder with 10 MAPS sensors (~ 2×2 cm each)

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

Mechanical support with kinematic mounts (insertion side)



Cantilevered support

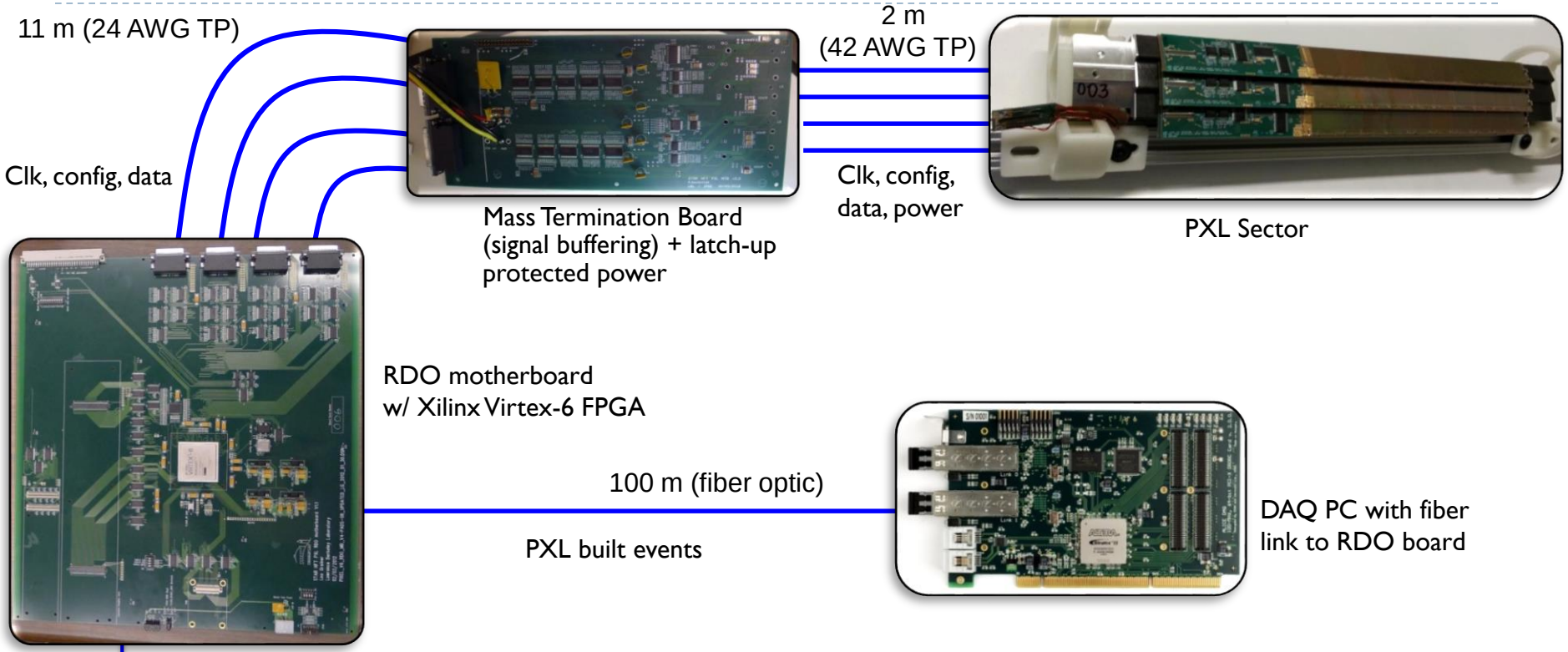


carbon fiber sector tubes (~ 200 μm thick)



STAR

# 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

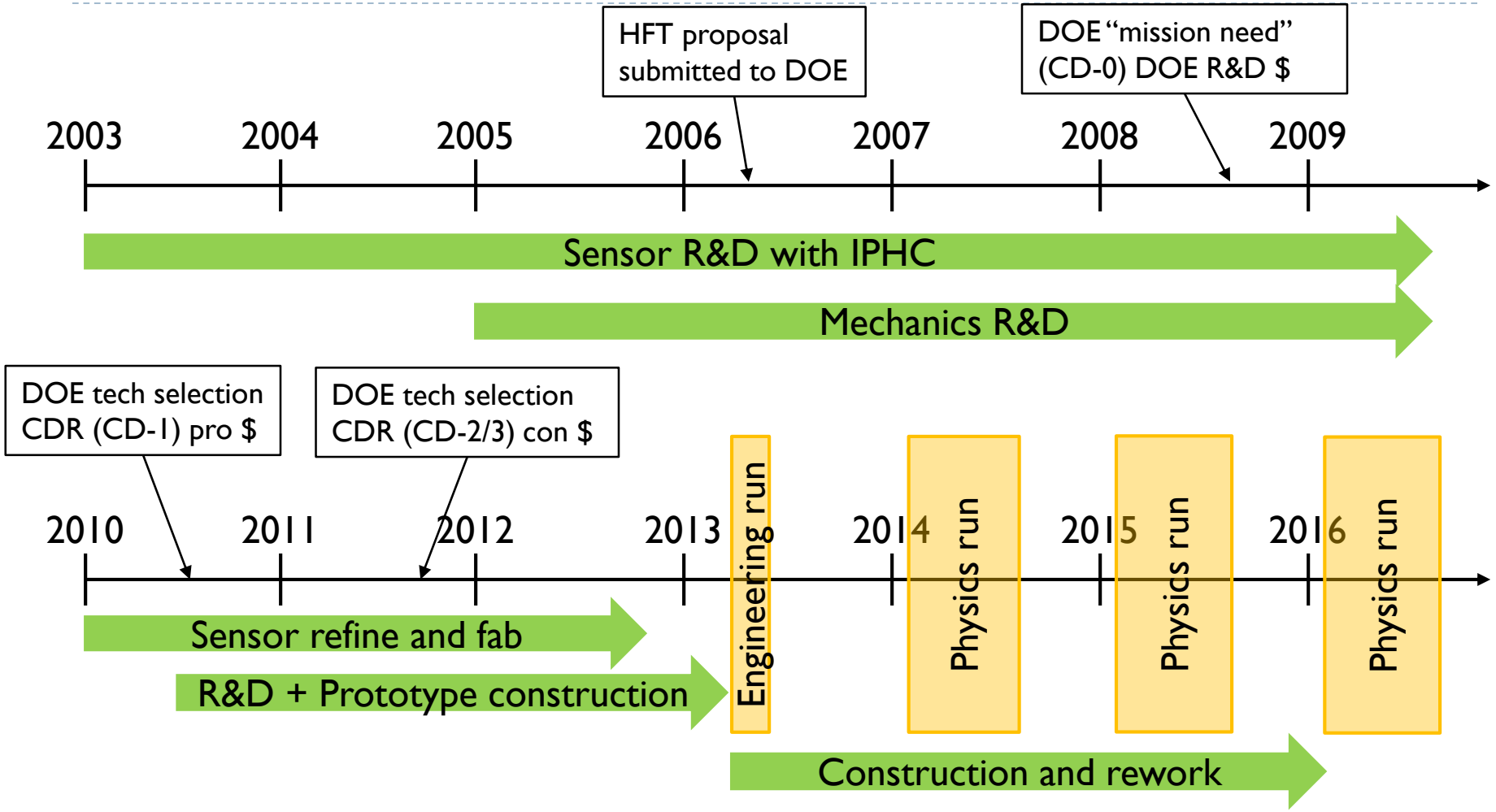
# PXL Design Parameters

| | |
|---|---|
| DCA Pointing resolution | (10 ⊕ 24 GeV/p·c) μm |
| Layers | Layer 1 at 2.8 cm radius<br>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<br>$2*10^{11}$ to $10^{12}$ 1MeV n eq/cm$^2$ |
| Rapid detector replacement | < 1 day |

- 356 M pixels on ~0.16 m$^2$ of Silicon
- Air cooling
- Sensors thinned to 50 μm

- PXL Project Timeline and runs

# PXL timeline




The HFT was removed from STAR after the completion of run 16 and put into storage.

# PXL data taking

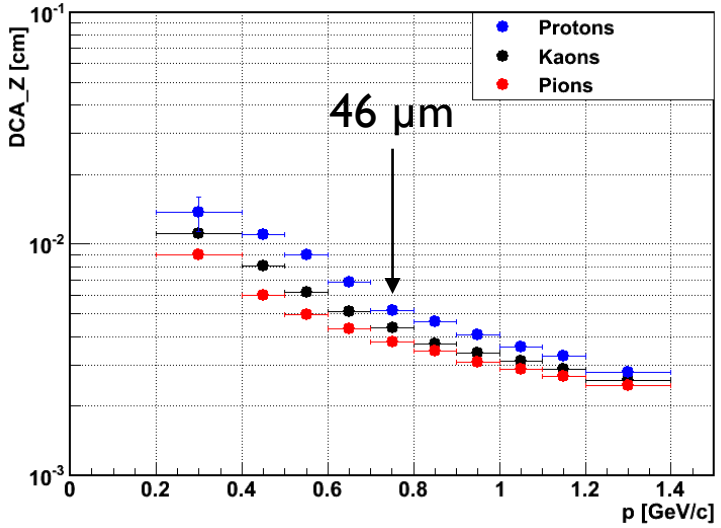
- Experimental program:
  - DOE approved a 3 year program focusing on D meson production. This is a relatively short program which requires that the detector produce good analyzable data from day 1. This requires significant amount of effort to install a well understood and controlled detector system of new technology and high complexity.
- 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

- Physics Running - Collected *minimum bias* events in 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

- PXL Performance and operational aspects

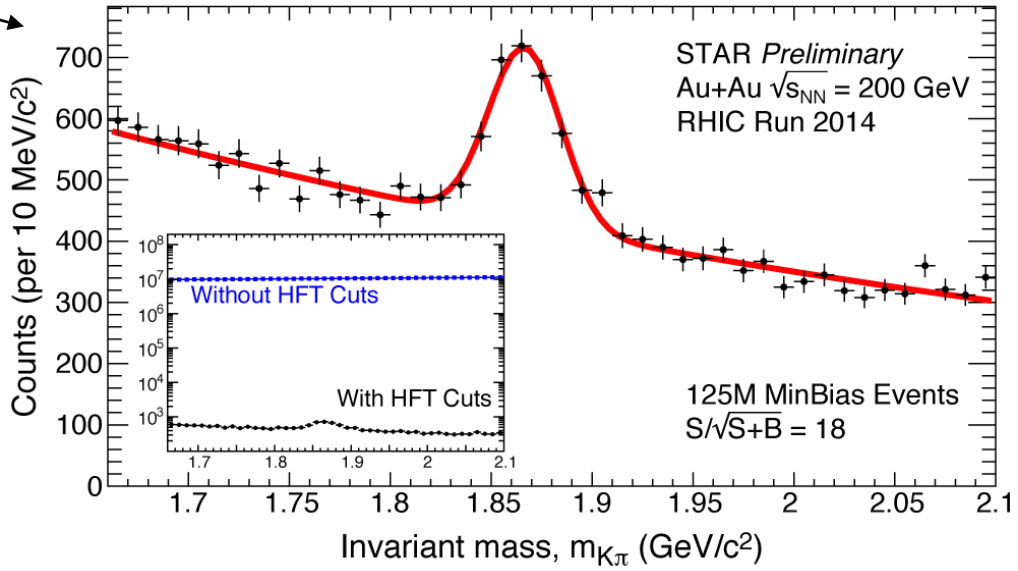
# HFT Performance from 2014 data

- 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 (partial event sample)*

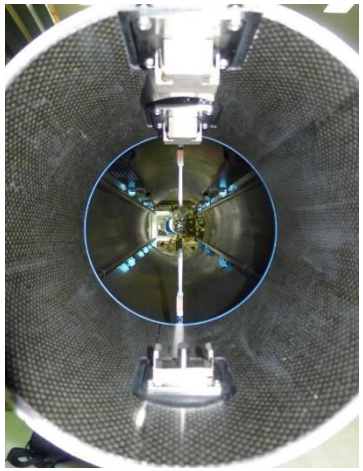
- Physics of D-meson productions
  - High significance signal
  - Nuclear modification factor $R_{AA}$
  - Collective flow $v_2$



# Operational Aspects

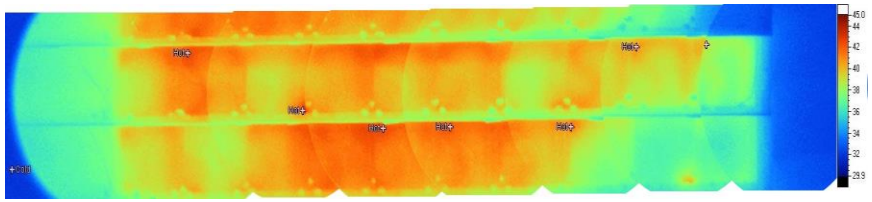
What worked **well** and what needed extra effort (after initial setup):

- 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 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.



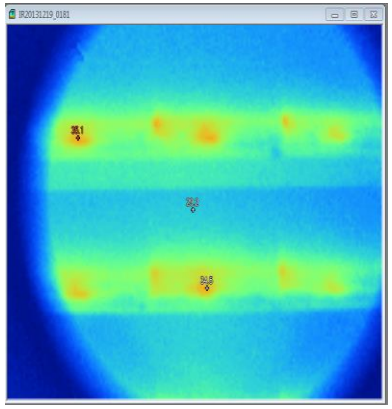
PXL Kinematic mounts

| | |
|---|---|
| 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

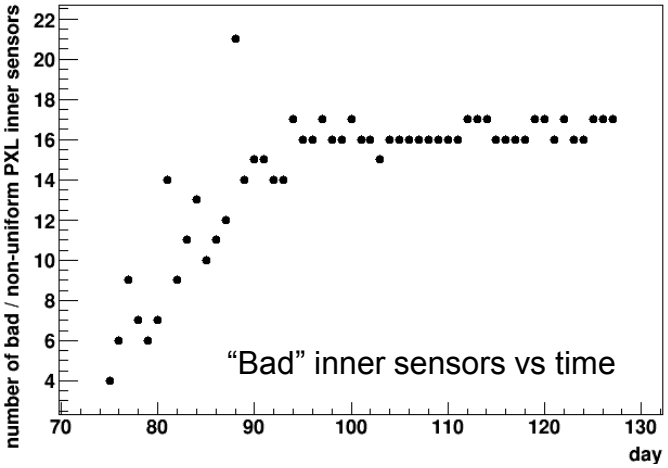
IR image of production PXL ladders. Max ΔT is 12˚ C from ambient.



# Operational Aspects

- Operational latch-up protection worked well limiting LU related sensor damage to a small number of sensors in a run. (more later in talk)
- Operational reset for SEU on a 15 minute schedule worked well.
- RDO worked well allowing trigger rates up to the STAR maximum (~1kHz) TPC rate.
- The detector in the system context, provided the required DCA pointing resolution and matching the simulations.

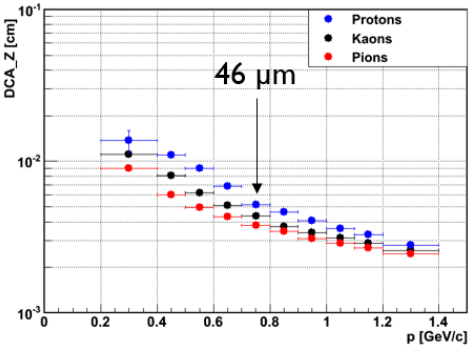
Run 14 data




Run display showing PXL 4% dead at 1.1kHz trigger rate

| Det | State | Dead | CPU% | Evts | Hz | kB/s | Err |
|---|---|---|---|---|---|---|---|
| TOF | RUNNING | 9 % | 15 | 62008 | 1552 | 18523 | 0 |
| BTOW | RUNNING | 3 % | 16 | 62254 | 1552 | 15196 | 0 |
| Trigger | RUNNING | 0 % | 0 | 62949 | 1562 | 5089 | 0 |
| ETOW | RUNNING | 3 % | 14 | 63151 | 1546 | 3252 | 0 |
| BSMD | RUNNING | 4 % | 18 | 6012 | 158 | 2095 | 0 |
| ESMD | RUNNING | 4 % | 51 | 62012 | 1552 | 28800 | 0 |
| TPX | RUNNING | 14 % | 56 | 63468 | 1563 | 973114 | 0 |
| PXL | RUNNING | 4 % | 20 | 42625 | 1098 | 148139 | 0 |
| MTD | RUNNING | 3 % | 13 | 62423 | 1554 | 1419 | 0 |
| IST | RUNNING | 5 % | 76 | 42361 | 1091 | 32911 | 0 |
| SST | RUNNING | 1 % | 13 | 297 | 7 | 5085 | 0 |

DCA pointing resolution



# Operational Aspects

What worked well and what needed **extra effort** (after initial setup):

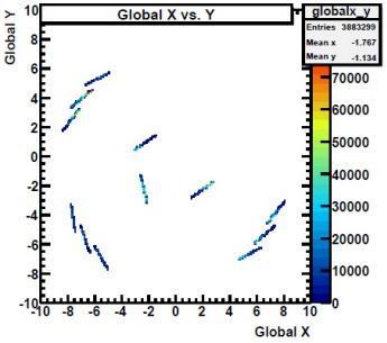
- Sensor damage due to latch-up related events caused a low rate of damaged sensors in the detector over a run. This required that we do repairs in the off times between runs. This was mitigated by having two operational detectors available so that a complete fresh detector was available at all times.
- A event decoder software problem discovered after the run14 data was analyzed required the re-processing of the run 14 data to achieve the full simulated efficiency.
- A RDO firmware bug introduced after run 14 lowered the efficiency for run 15. This was discovered at the beginning of run16 and corrected so that the run16 data was not significantly affected.

Included in "lessons learned" section

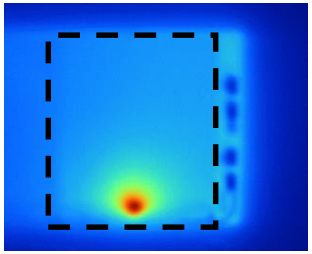
- Lessons learned

# Engineering run 2013

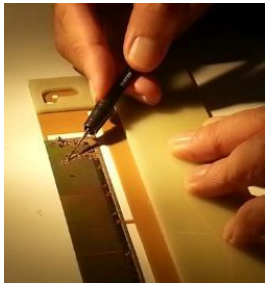
- 3 prototype sectors installed at end of 2013 run.
- PXL Engineering Run assembly crucial to deal with a number of unexpected issues




Engineering run geometry



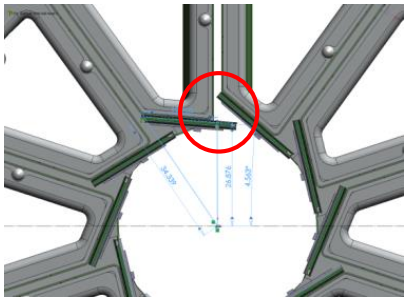
Sensor IR picture



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, adhesive extended.

- 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



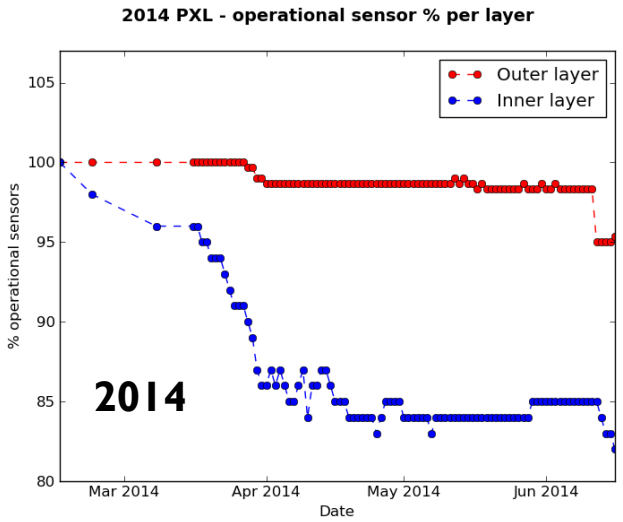
Inner layer design

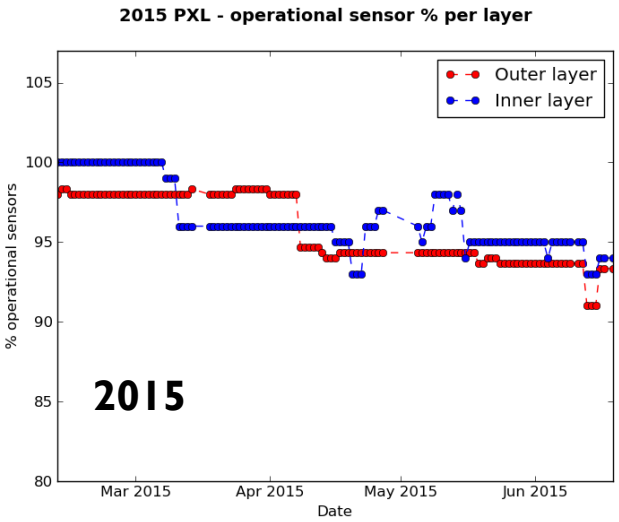
- After the engineering run added functionality to the MTB:
  - remote setting of LU threshold and ladder power supply voltage + current and voltage monitoring

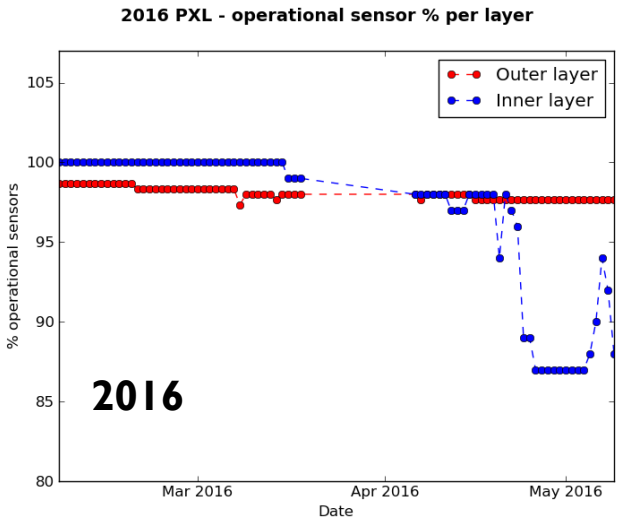
# LU Damage evolution

| 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



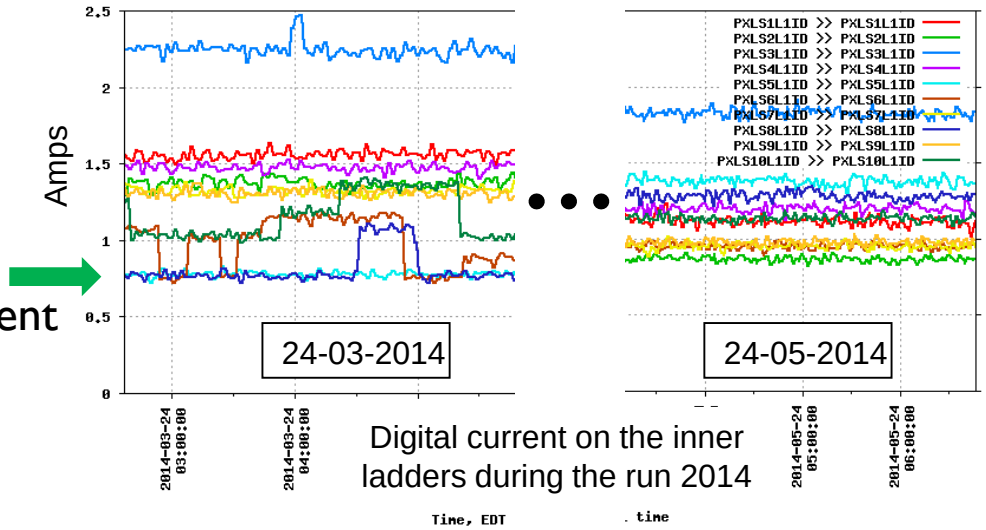



# LU damage observables (run 14)

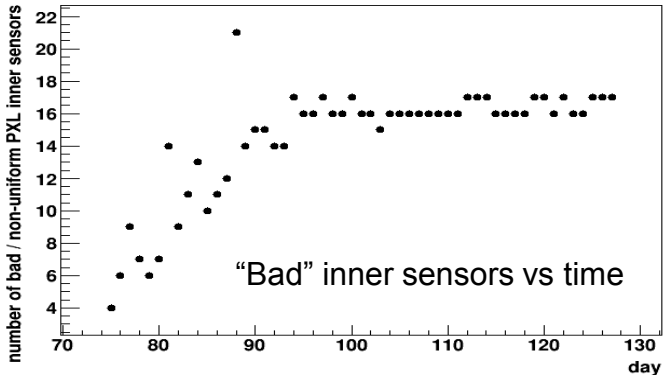
Observed increased digital operating currents for inner ladders after over-current protection events
(LU threshold = 300mA over operating current)

Normal operating current

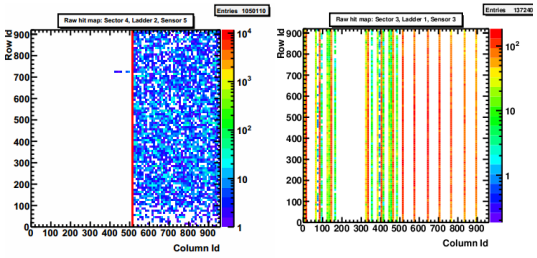


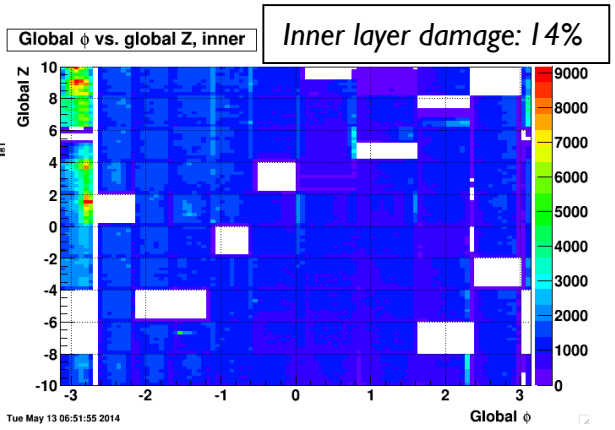

Digital current on the inner ladders during the run 2014

After the first 2 weeks of running we set the LU protection current threshold to be 120 mA above the ladder operating current and the damage rate was very significantly reduced.




Sensor damage profiles



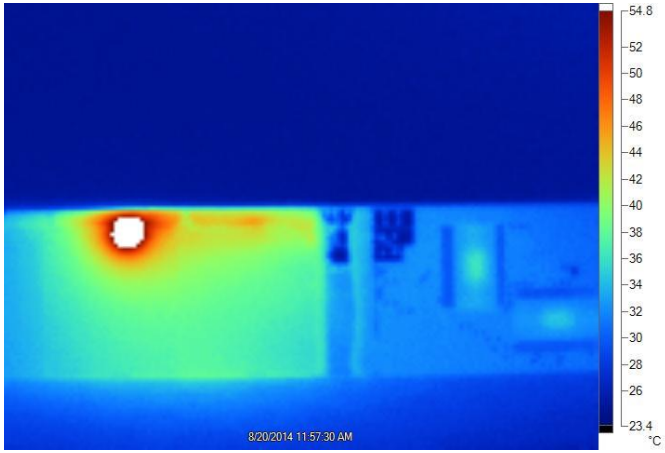



# Run 14 Damage analysis

*The sensor development testing program tested LU on full thickness sensors and measured a cross section consistent with the measured LU recoveries recorded on the detector. The damage cross section is too low to easily measure with individual sensors based testing.*

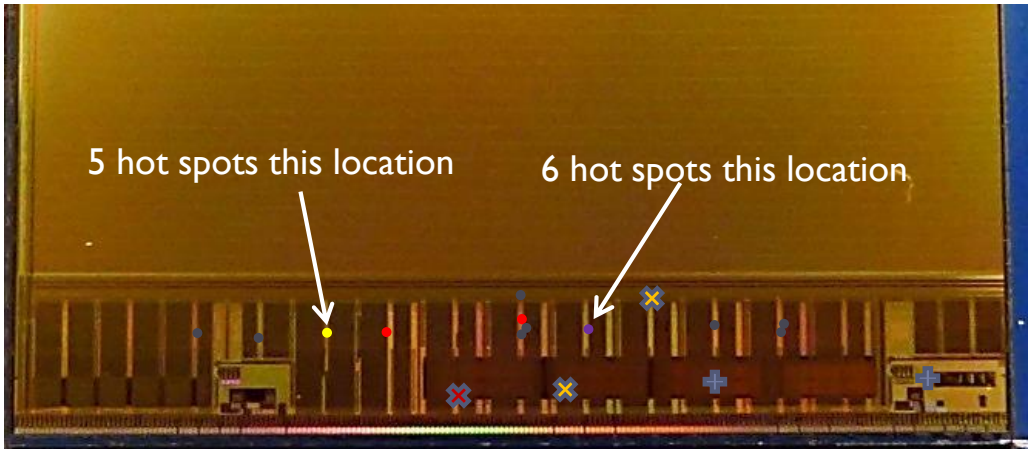
- Post run examination of damaged ladders showed IR "hot spots" giving the location of damage on the sensors.

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




50 um thinned silicon
Temperatures from 55-100 C

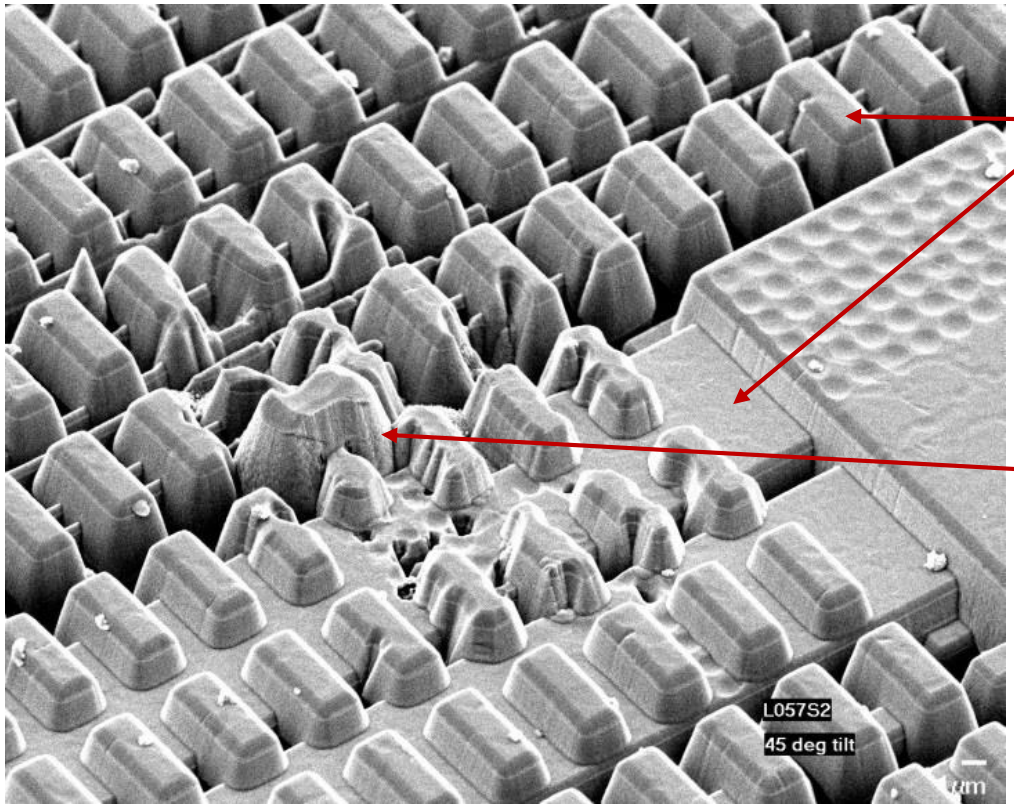
Hot spots were NOT randomly distributed and favored particular locations in the digital section.




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

# Run 14 Damage analysis

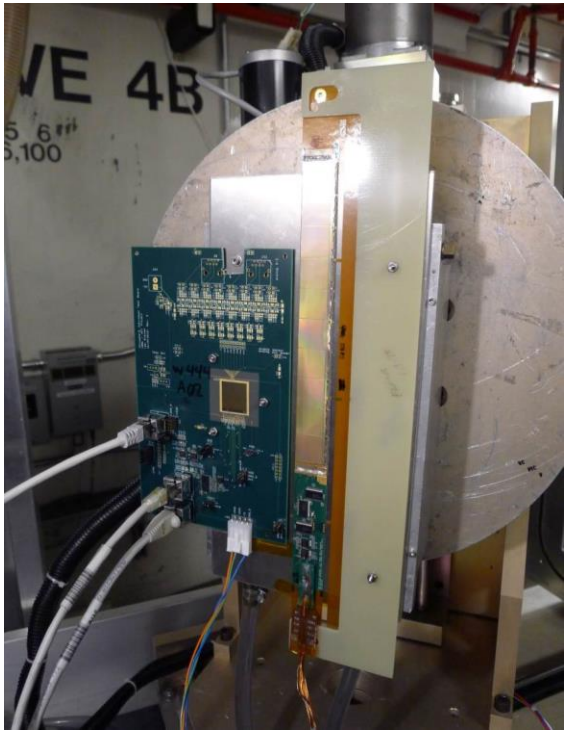
- Damaged sensors were plasma etched and then examined at the damage locations with a SEM. The damage is clearly visible and appears to show melted silicon in the hot spot locations.



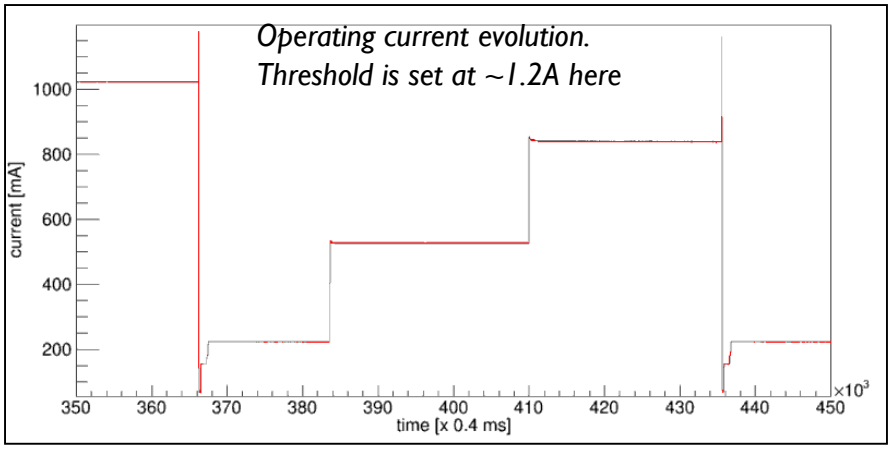

Metal layers (stop the plasma etching)

Melted silicon

# Run 14 Damage analysis



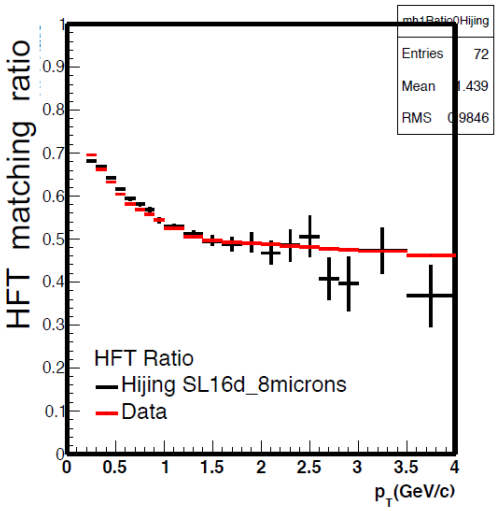
- Testing at LBNL BASE facility with heavy ions and protons individual sensors both 50um and 700um thick and PXL ladders.
- Observed current limited LU of ~300 mA in all sensors.

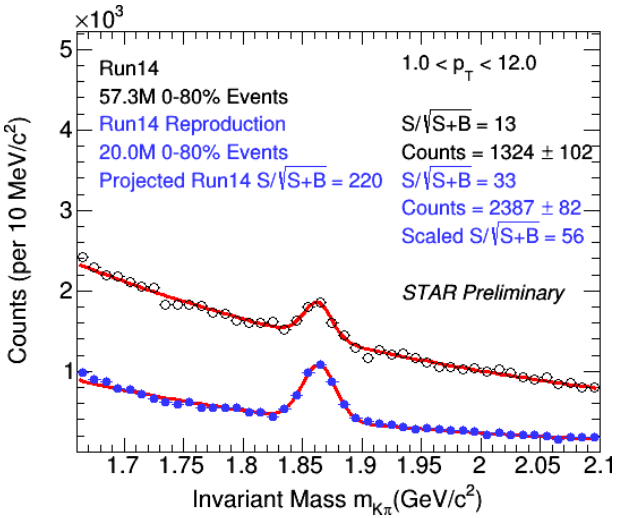



- We were able to reproduce the damage on thinned 50um sensors with high flux protons.
- Despite all attempts with HI and protons, we were unable to damage 700um thick sensors.
- We conjecture that there are a small number of sites that have high current LUs. In the thick sensors there is enough thermal conductivity to keep the sensors from being damaged with the energy available for a LU event. (Energy from bypass capacitors)

# 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 performance, which now matches the simulation



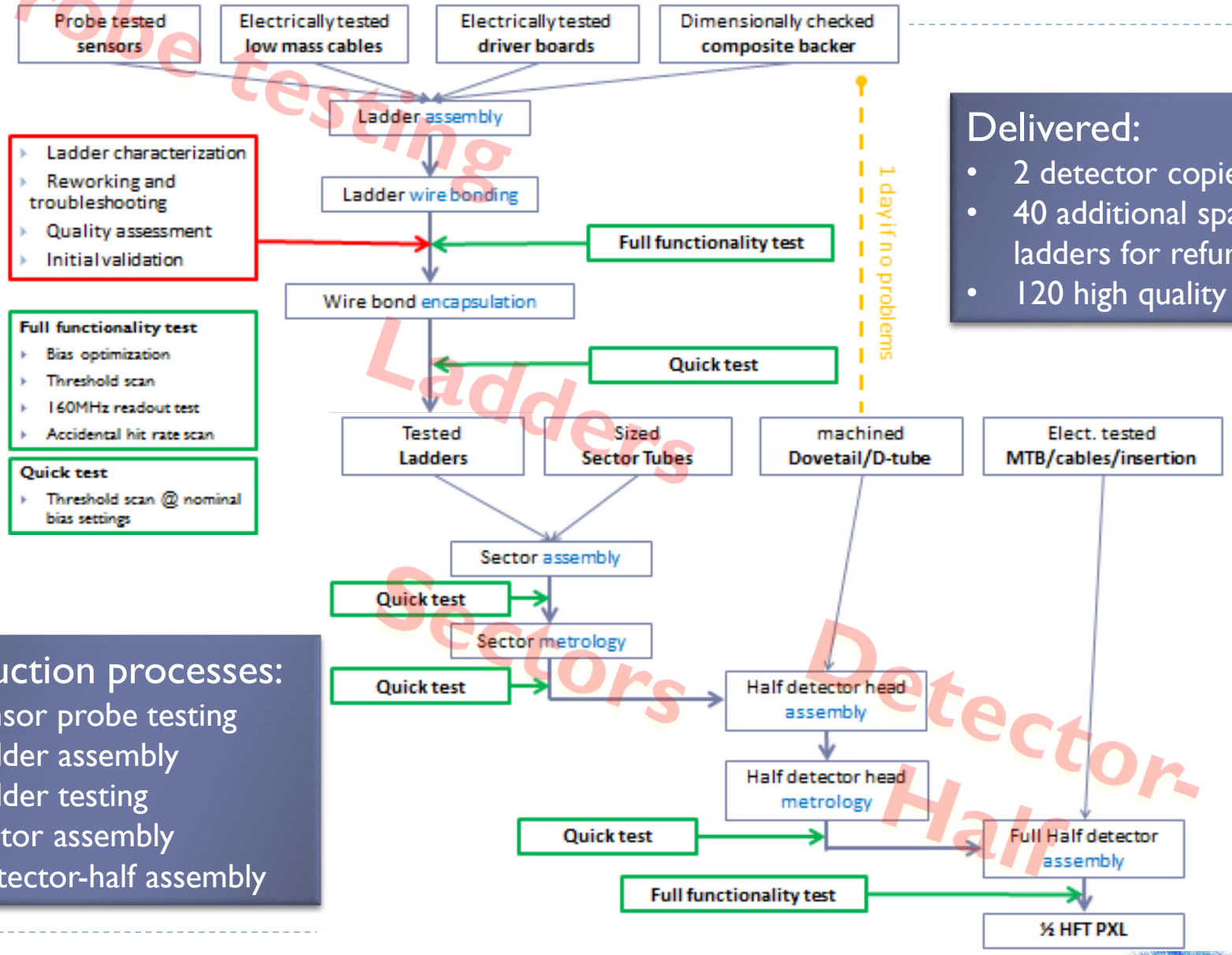

- Readout firmware issue - 2015 data, matching inefficiency
  - A subtle bug introduced by a change in the PXL RDO firmware led to an efficiency loss in the 2015 Run data (consequence still under investigation)
  - The extensive tests with pattern data and the performance of full detector calibrations 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 fixing

# Conclusions

- The 3 year physics program of the first MAPS based vertex detector at a collider has been successfully completed and the performance of the PXL detector meets the DCA pointing resolution requirements and has enabled STAR to perform direct topological reconstruction of open charm hadrons.
- The operational aspects of the PXL detector design have been demonstrated to work well in the RHIC environment despite a low rate of LU induced damage to the sensors.
- The 2013 Engineering Run was crucial for identifying pre-production problems and allowed us to optimize the designs for the production detectors.
- As expected for a detector subject to beam-induced damage, the PXL construction phase continued throughout the entire detector life for yearly refurbishment and optimization.
- The PXL experience demonstrates the difficulty in of tuning readout firmware and reconstruction software in the limited time available in a short duration physics program.

# Backup slides

# PXL Production, Assembly and QA



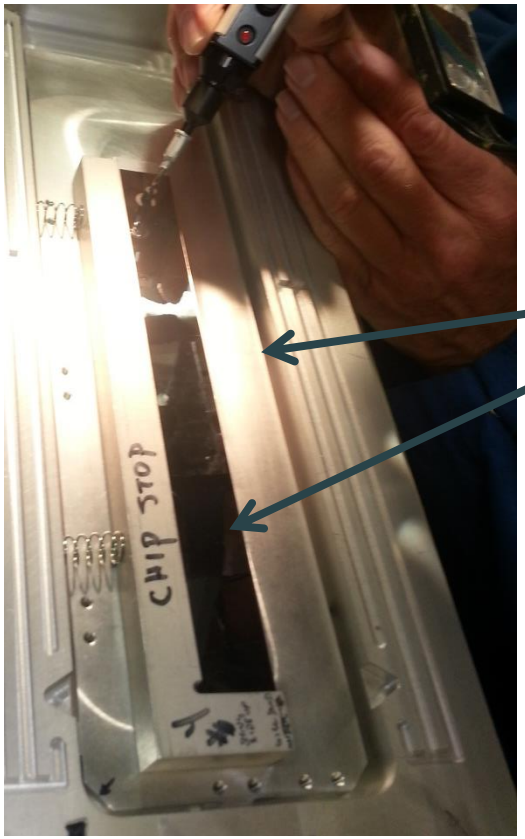

**Delivered:**

- 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

# Ladder Assembly



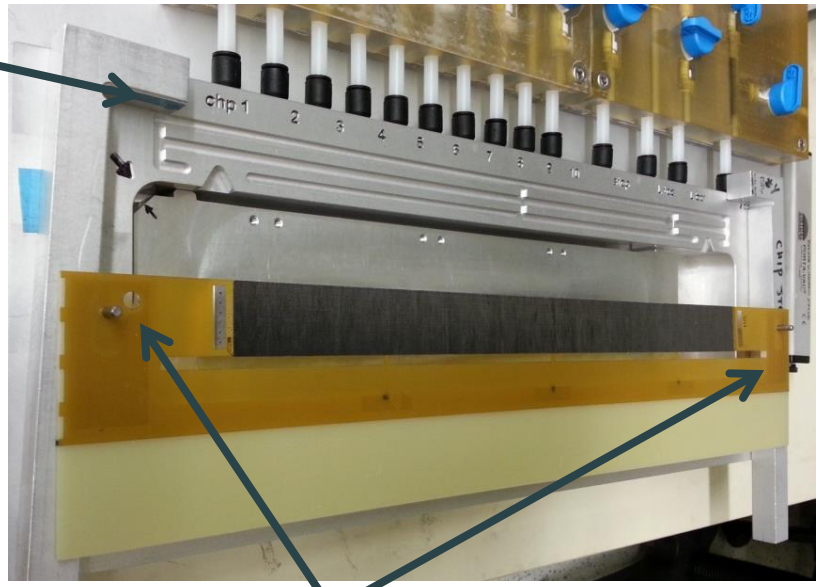

Sensor positioning

Precision vacuum chuck fixtures to position sensors by hand

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

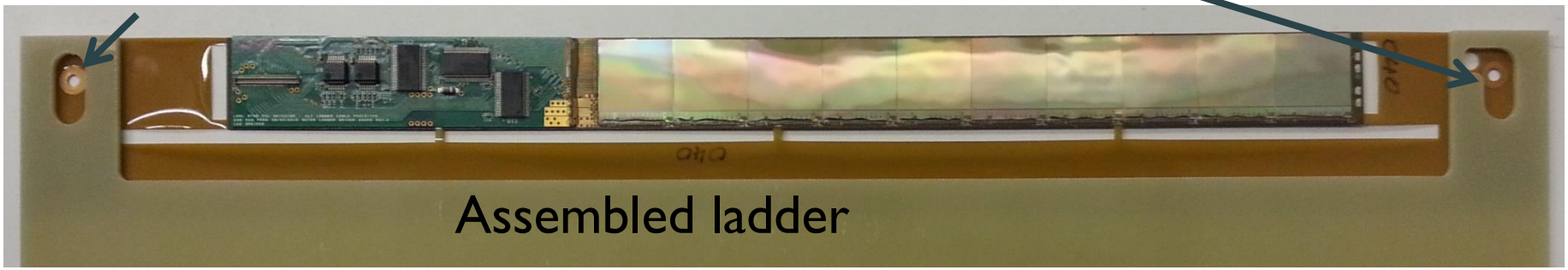
Weights taken at all assembly steps to track material and as QA.

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



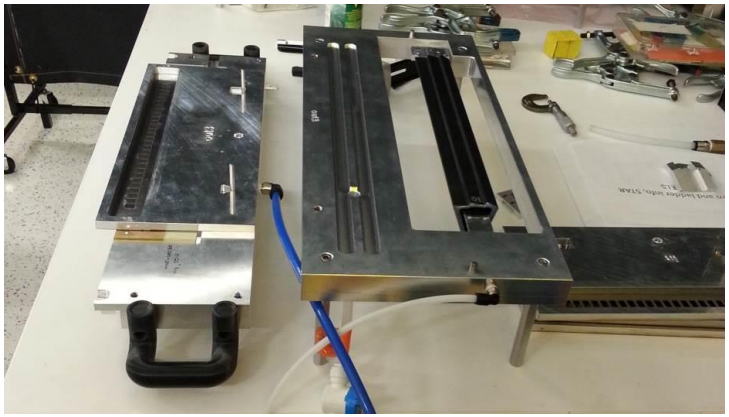

Cable reference holes for assembly

FR-4 Handler



Assembled ladder

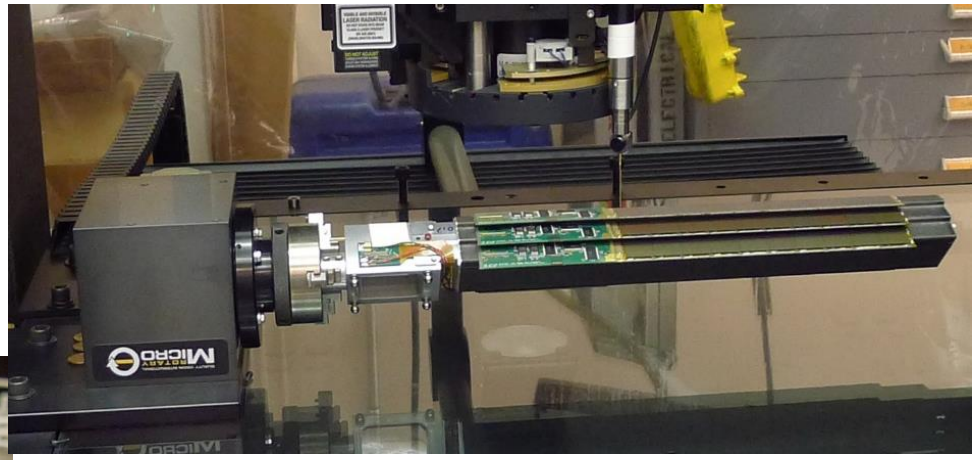
# From ladders to sectors… to detector halves



*Sector assembly fixture*

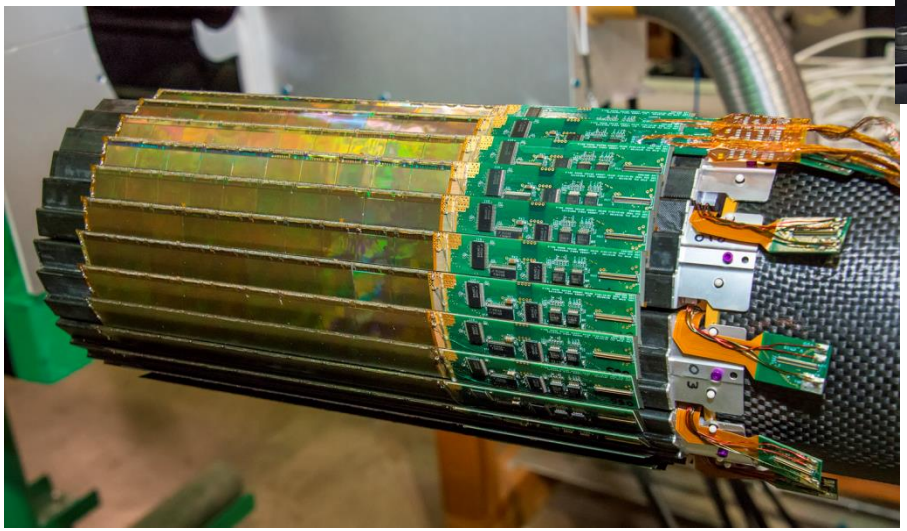
## Sectors

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



*Sector in the metrology setup*

*A detector half*



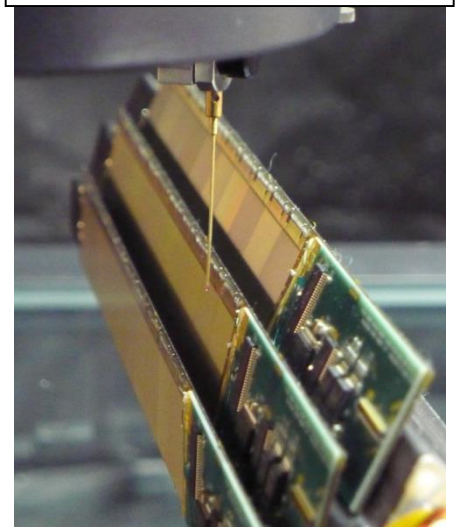
## Detector half

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

→ Detector half mapped

# PXL Position Control

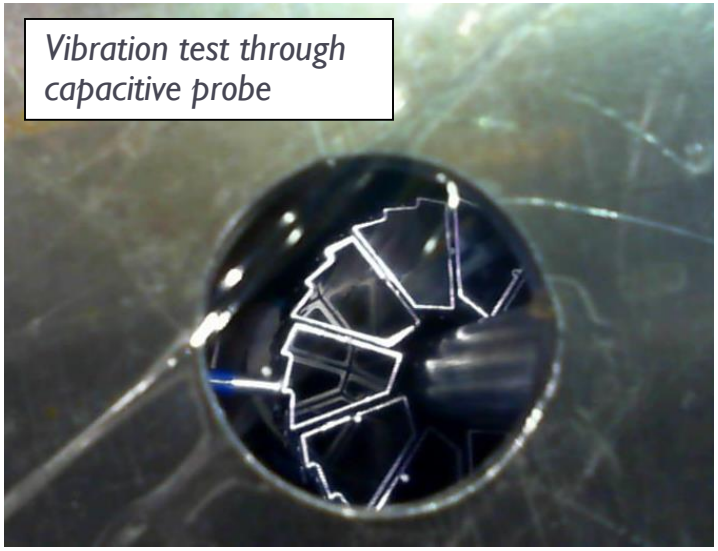
*Sector in the metrology setup*



- 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*

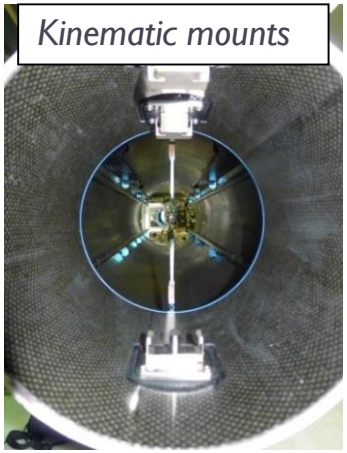


- Position stability
  - Vibration at air cooling full flow: ~5 μm RMS
  - Stable displacement at full air flow: ~30 μm
  - Stable displacement at power on: ~5 μm

→ Global hit position resolution: ~ 6.2 μm

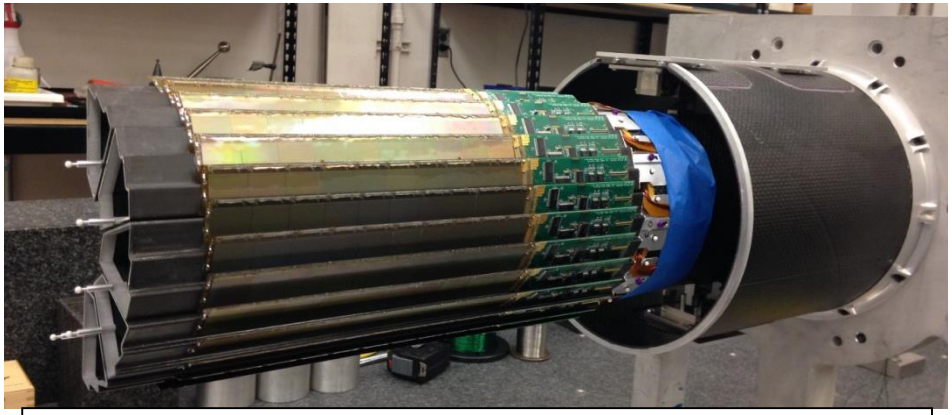
HFT DCA pointing resolution: **(10 ⊕ 24/p) μm**

# PXL Installation in STAR

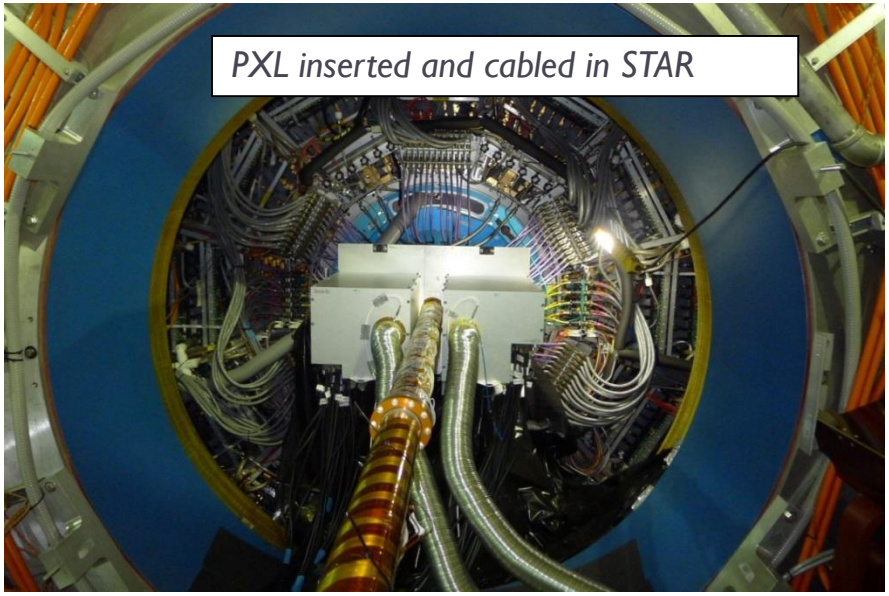

*Kinematic mounts*

Novel insertion approach

- Inserted along rails and locked into a kinematic mount inside the support structure


*duplicate, truncated PXL support tube with kinematic mounts*

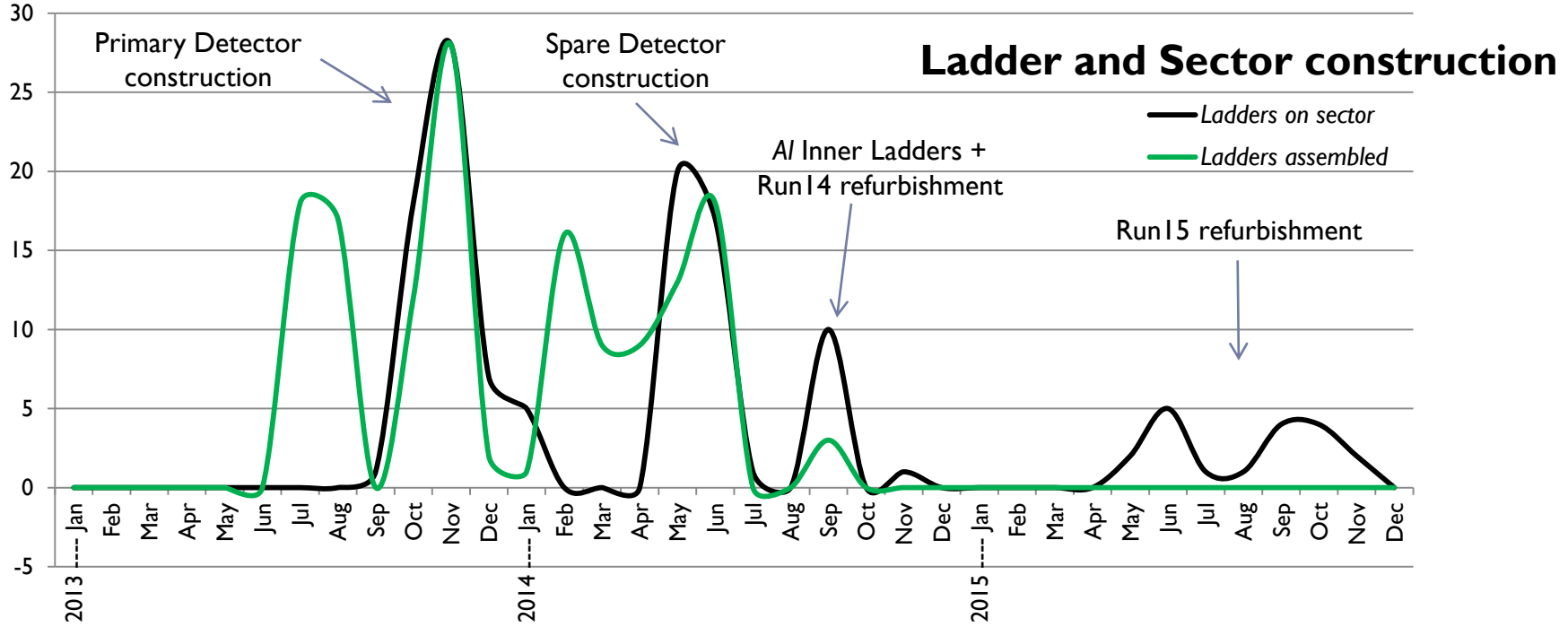
*Insertion in STAR*


*PXL inserted and cabled in STAR*

# PXL production timeline

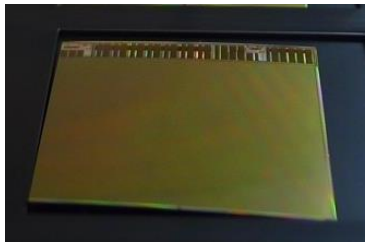
- Delivered:
  - 2014 Run: Primary Detector, 2 *aluminum cable* inner ladders, rest in *copper*
  - 2015-2016 Runs: Two Detector copies, all inner ladders in *aluminum*
- Sector refurbishment:
  - After each Run for *latch-up* induced damage
  - After over-powering accident during 2015 Run installation

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



# PXL Parts & Material Budget

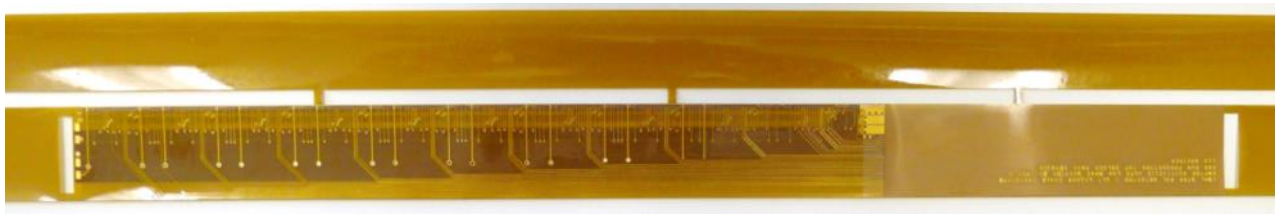
- Thinned Sensor
  - 50 μm
  - 0.068% $X_0$



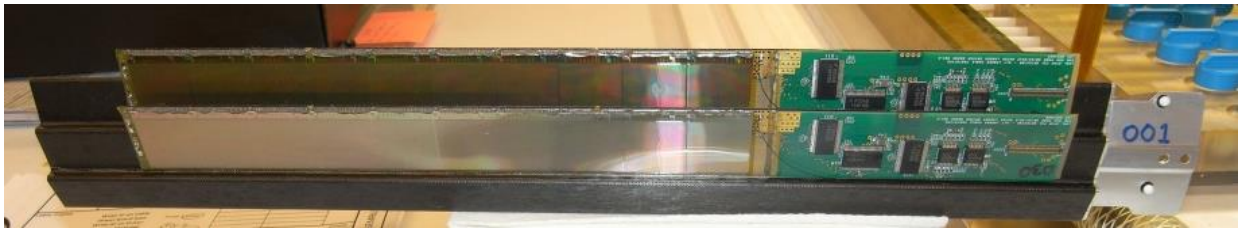
- Curved sensor
- 40-60% yield after thinning, dicing and probe testing
- Fully characterized before installation

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

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



- 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:
**$(10 \oplus 24/p)$ μm**