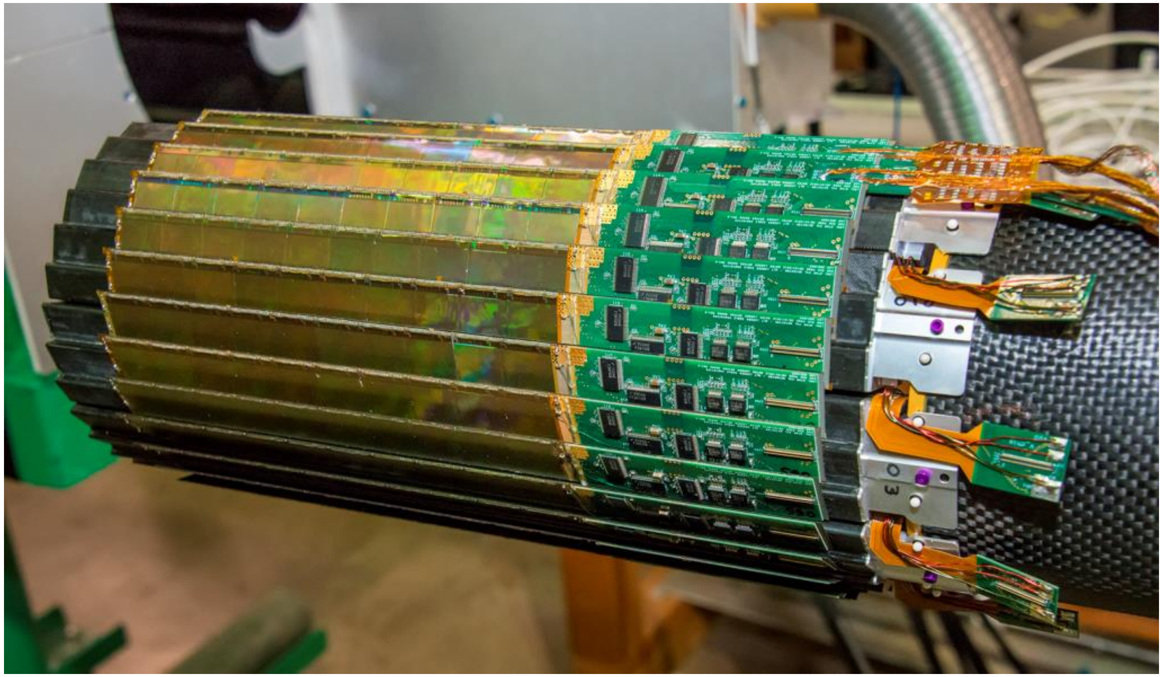
The STAR Heavy Flavor Tracker (HFT)

(with a focus on the MAPS based PXL detector)



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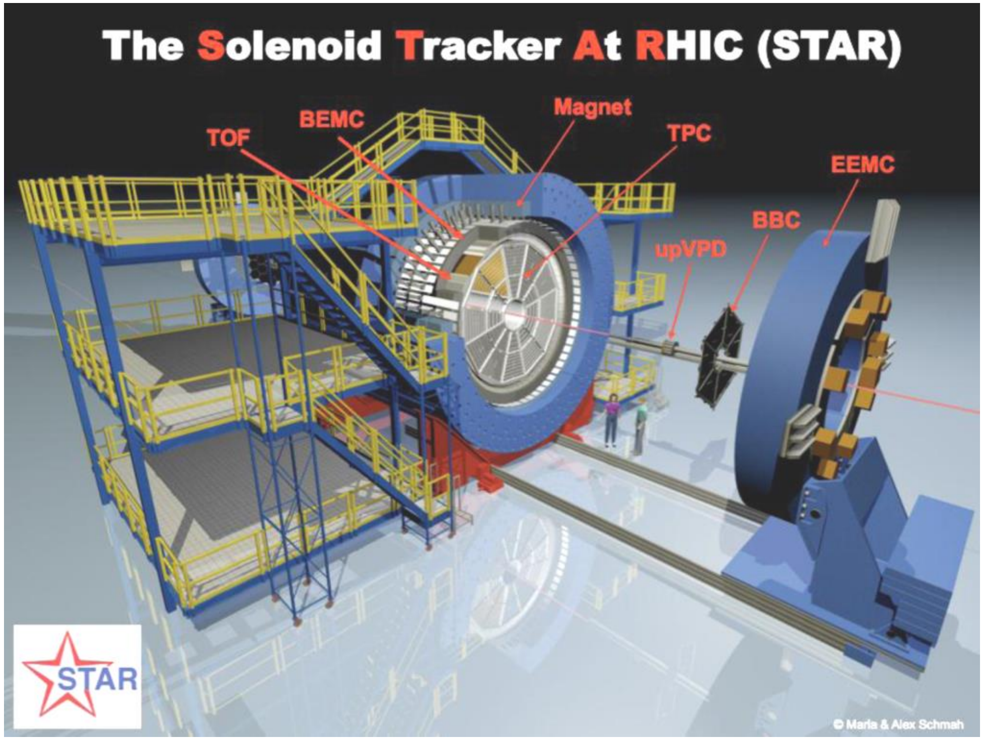
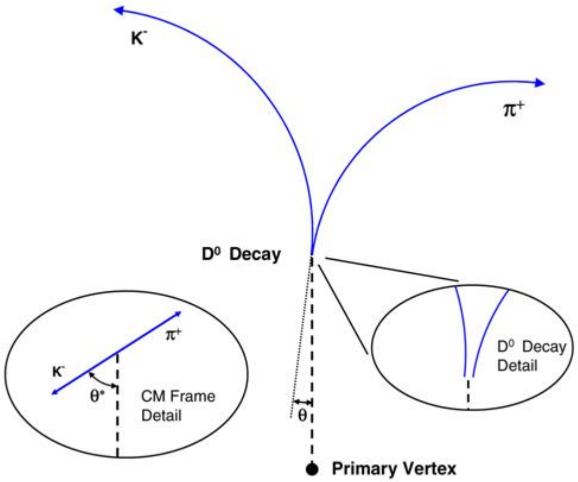
Talk Outline

- HFT Design
- Construction & Installation
- Run Status
- First Results
- Damage & Remediation
- Summary & Outlook

STAR detector at RHIC

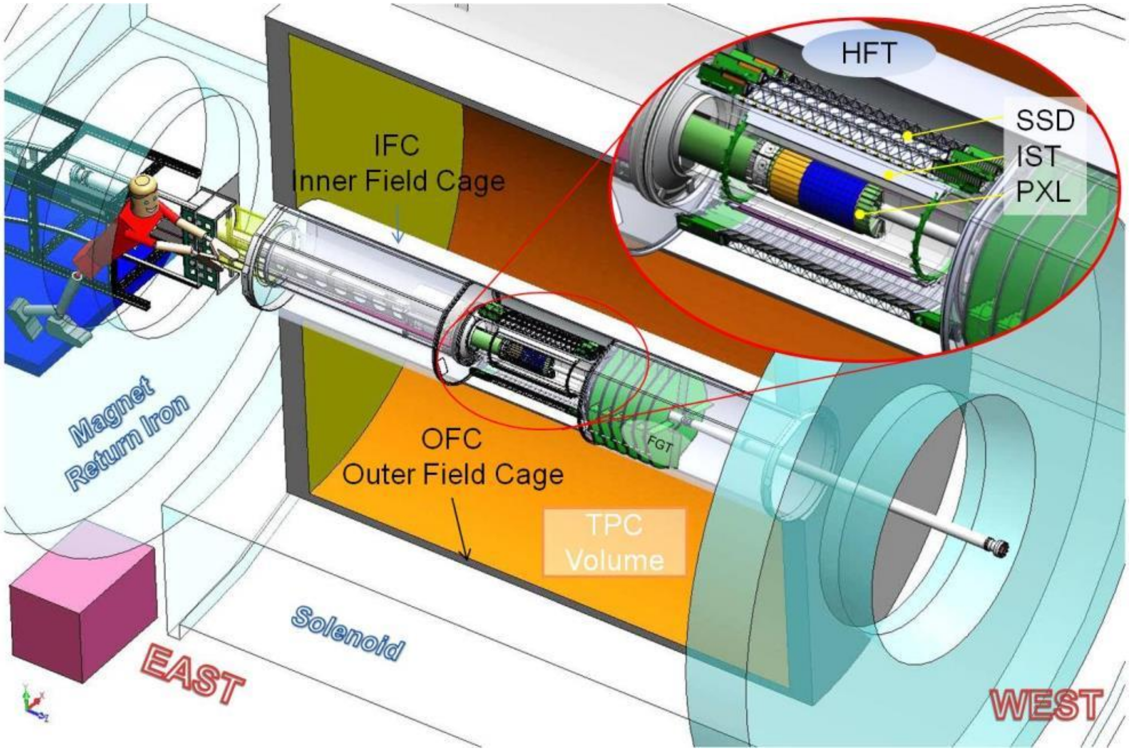
- **STAR** is an existing detector that has operated for 14 years at RHIC
- The "**H**eavy **F**lavor **T**racker" is a newly installed upgrade to the inner tracking system of STAR





- The HFT has fine spatial resolution that will allow direct topological identification of short-lived particles with heavy quarks, such as the D^0 and D* meson by identifying their decay vertices displaced ~120 µm from the primary vertex

STAR Heavy Flavor Tracker (HFT)



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

HFT – Heavy Flavor Tracker

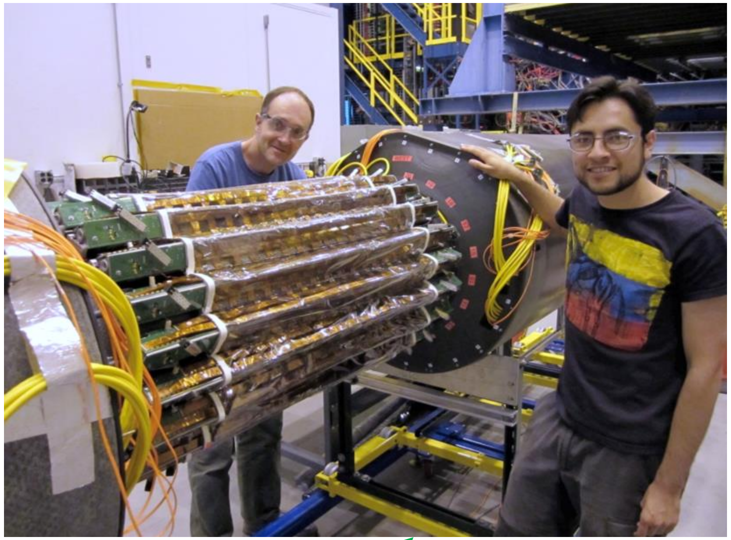
- **SSD – Silicon Strip Detector**
- **IST – Intermediate Silicon Tracker**
- **PXL – Pixel Detector**

We track inward from the TPC with graded resolution:

TPC → ~1mm → SSD → ~300µm → IST → ~250µm → PXL → <30µm → vertex

HFT Components

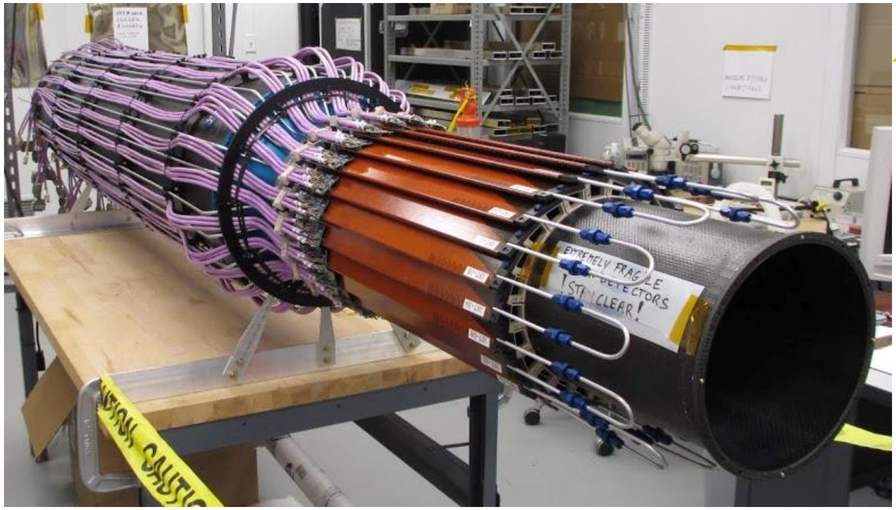
- Silicon Strip Detector:
  - Double sided silicon strip modules with 95 μm pitch
  - Existing detector with new faster electronics
  - Radius: 22cm

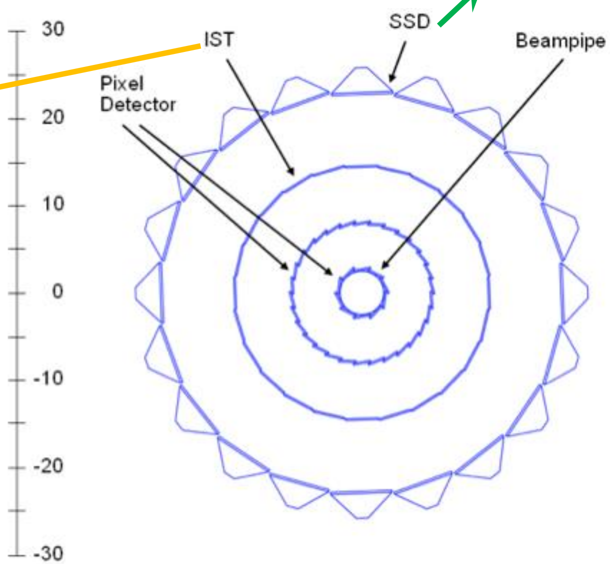


- Intermediate Silicon Tracker:
  - Single sided double-metal silicon pad with 600μm x 6mm pitch
  - Radius 14cm

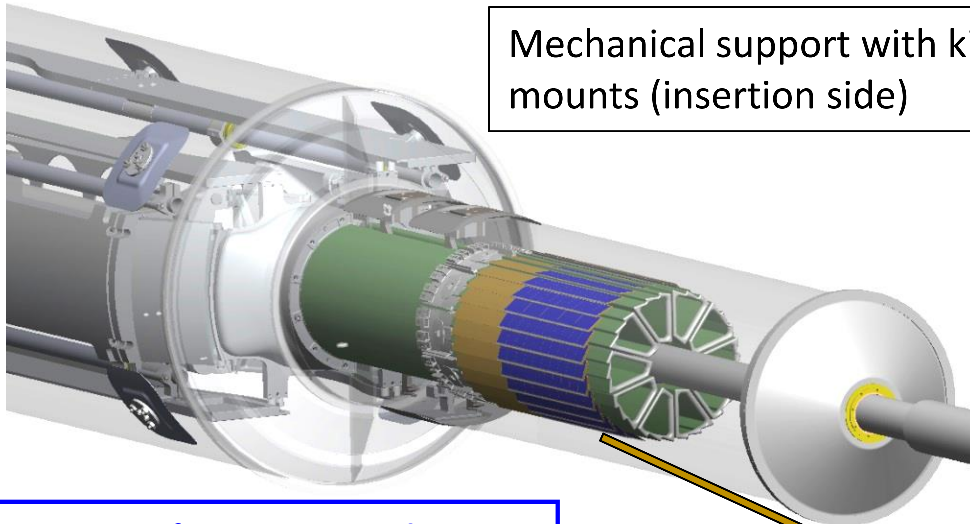
SSD and IST detector layers guide tracks from the TPC to the innermost layers of the HFT:

- PiXeL Detector:
  - 2 layers at radius 2.8cm and 8 cm





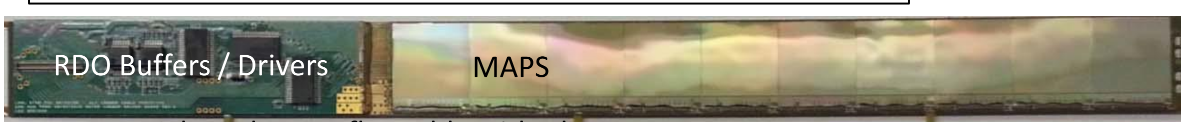
PXL Detector Design



Mechanical support with kinematic mounts (insertion side)

Insertion from one side
2 layers
10 sectors total (in 2 halves)
4 ladders/sector

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



2-layer kapton flex cable with Al traces

20 cm

carbon fiber sector tubes (~ 200 μm thick)

Detector Design Parameters

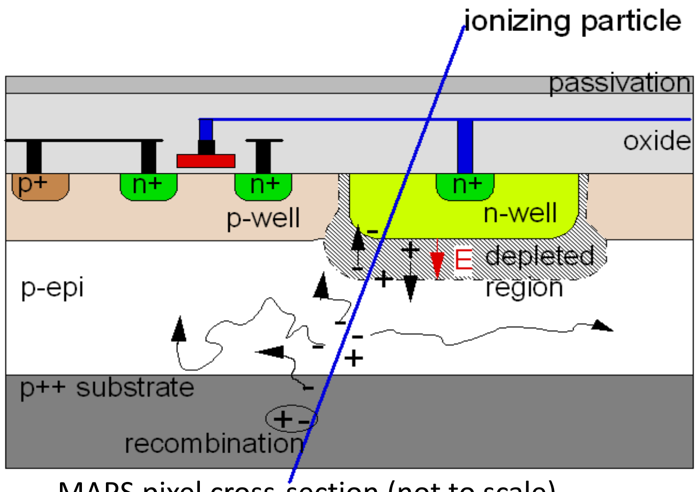
DCA Pointing resolution *	(12 ⊕ 24 GeV/p·c) μm
Layers	Layer 1 at 2.8 cm radius Layer 2 at 8 cm radius
Pixel size	20.7 μm X 20.7 μm
Hit resolution	3.7 μm (6 μm geometric)
Position stability	6 μm rms (20 μm envelope)
Radiation length first layer	X/X_0 = 0.39% (Al conductor cable)
Number of pixels	356 M
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

* Pointing resolution is limited by MCS and mechanical stability

Monolithic Active Pixel Sensor "*Ultimate-2*"

STAR HFT

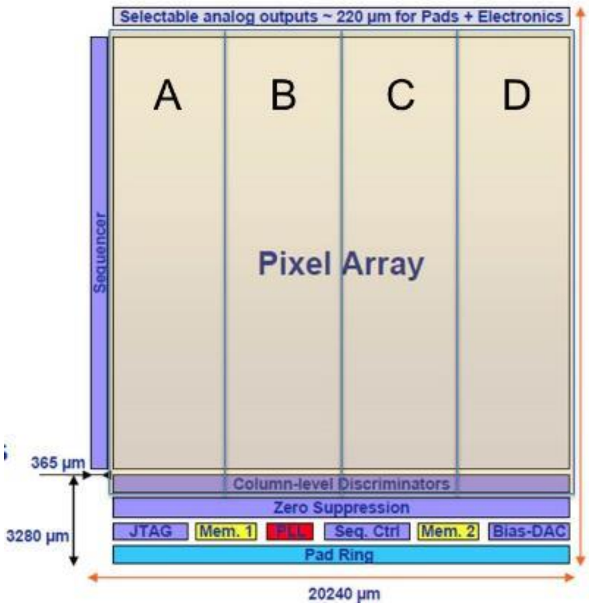


MAPS pixel cross-section (not to scale)

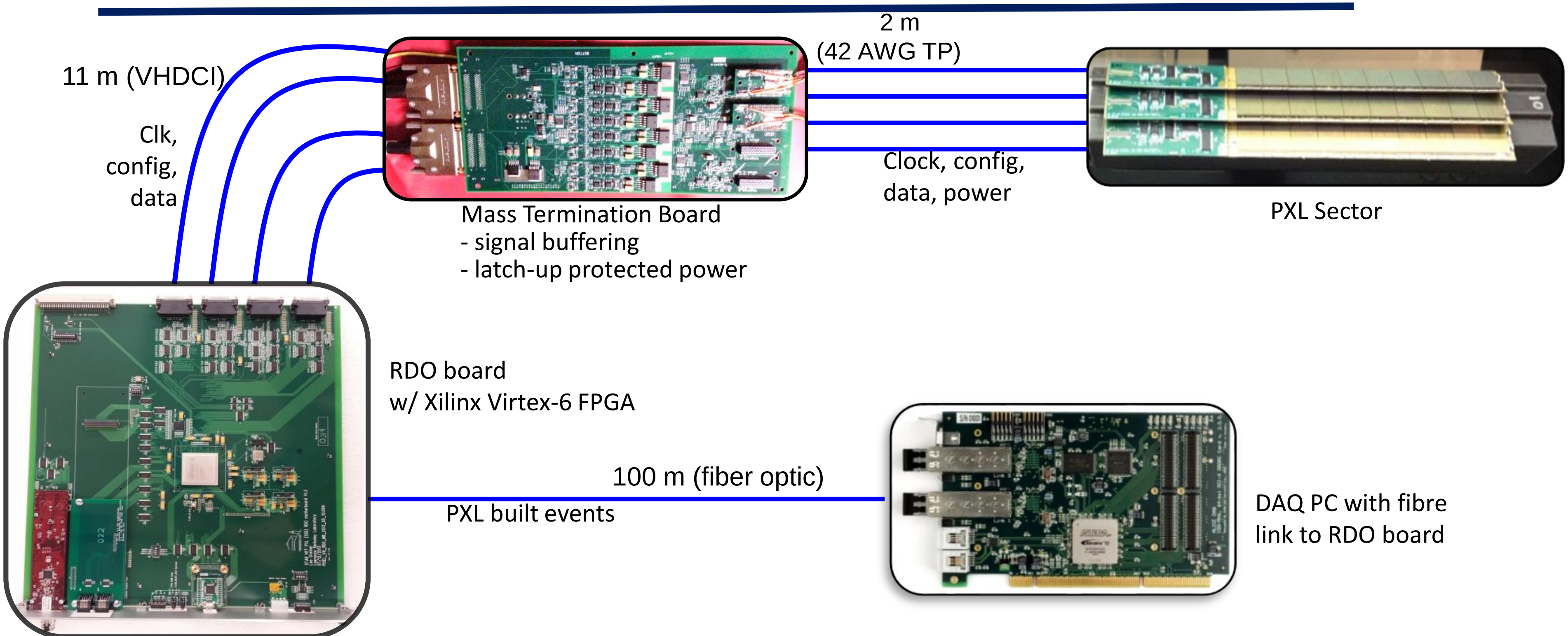
- Reticle size ~ 2cm x 2cm
  - Pixel pitch 20.7 um
  - 928 rows x 960 column array (~890k pixels)
- Power dissipation ~170mW/cm^2 @ 3.3V (air cooling)
- Short integration time 185.6 µs
- Sensors thinned to 50 µm
- Hi-Res Si option for increased S/N and radiation tolerance

3rd generation sensor developed for the PXL detector by the PICSEL group of IPHC, Strasbourg, optimized for the STAR environment

- In pixel CDS
- Discriminators at the end of each column
- 4 sub-arrays to help with process variation
- Column-parallel readout
- Integrated zero suppression and run-length encoding on rows (up to 9 hits/row)
- Ping-pong memory for frame readout (~1500 words)
- 2 LVDS serial data outputs @ 160MHz
- JTAG configuration of many internal parameters



Sector Readout Electronics Chain



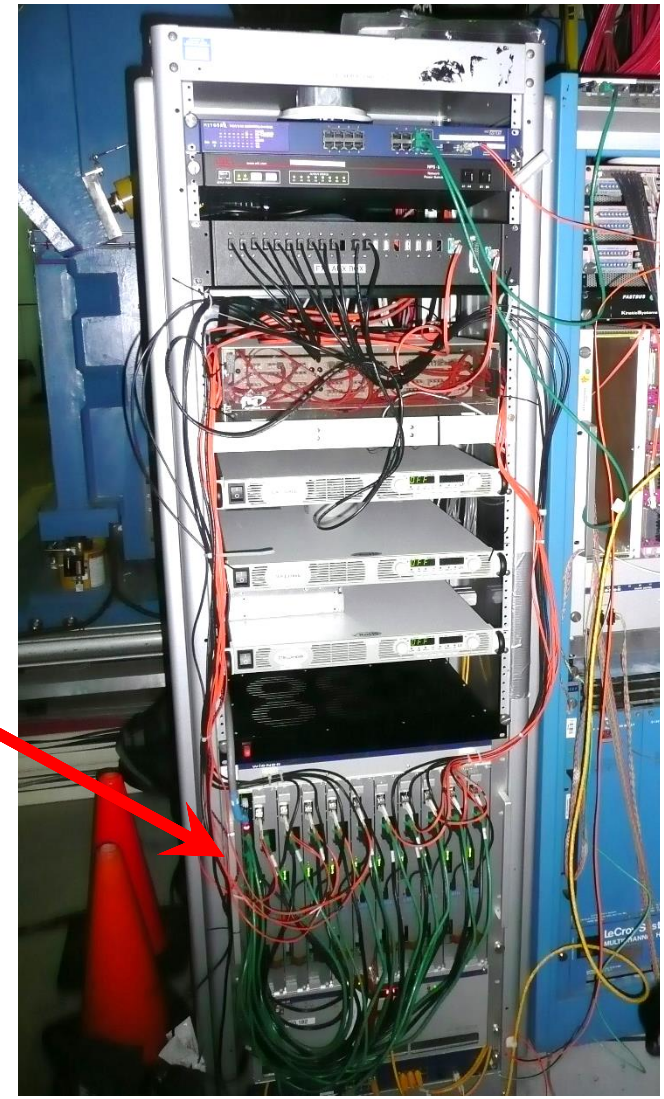
Trigger,
Slow control,
Configuration,
etc.

Existing STAR infrastructure

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 Electronics

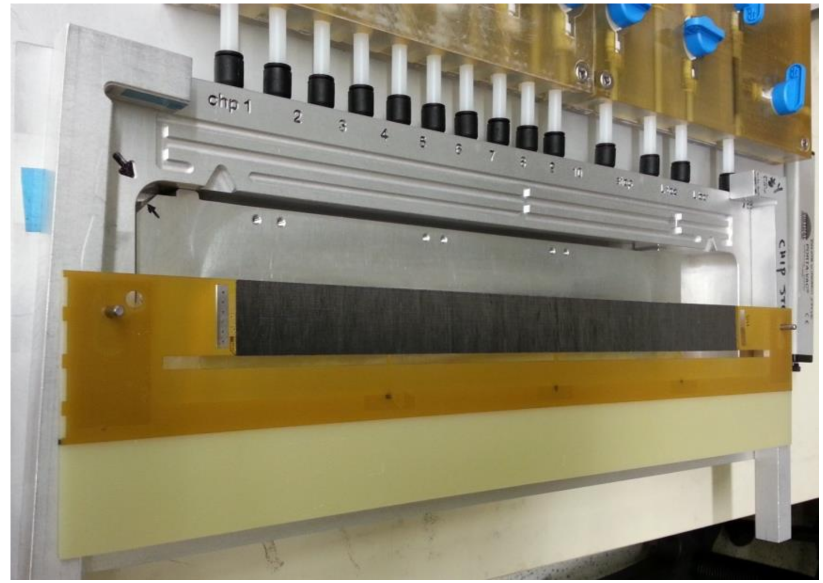


356 M pixel readout in a single 9U size crate

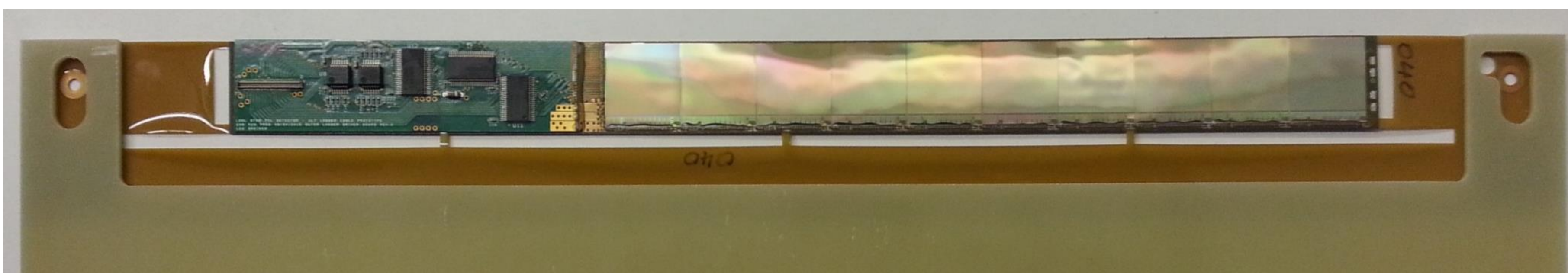
Ladder Assembly

Sensor positioning

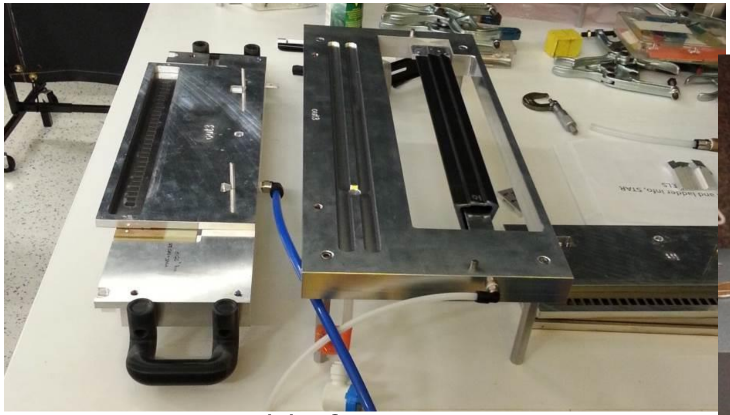
Precision vacuum chuck fixtures to position sensors



Assembled ladder

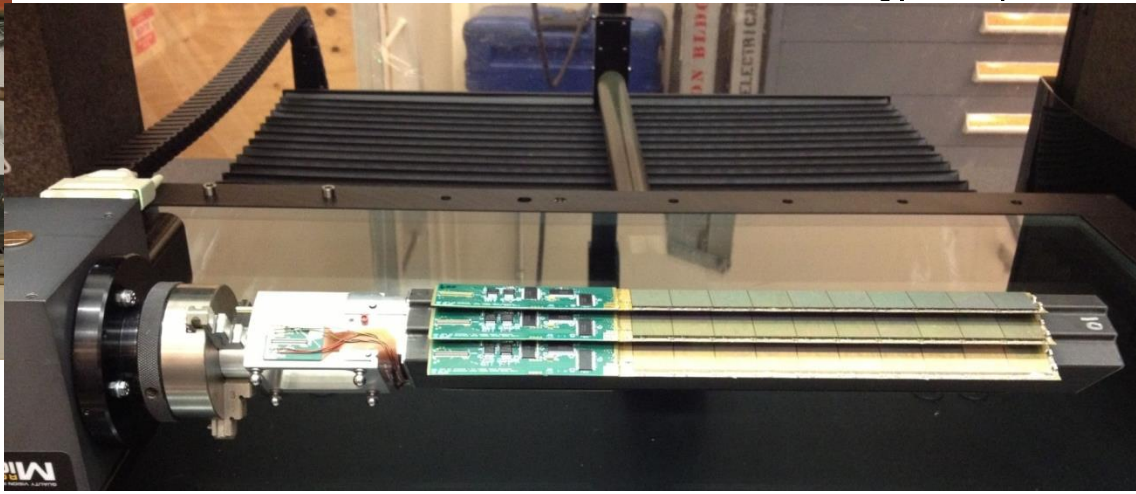


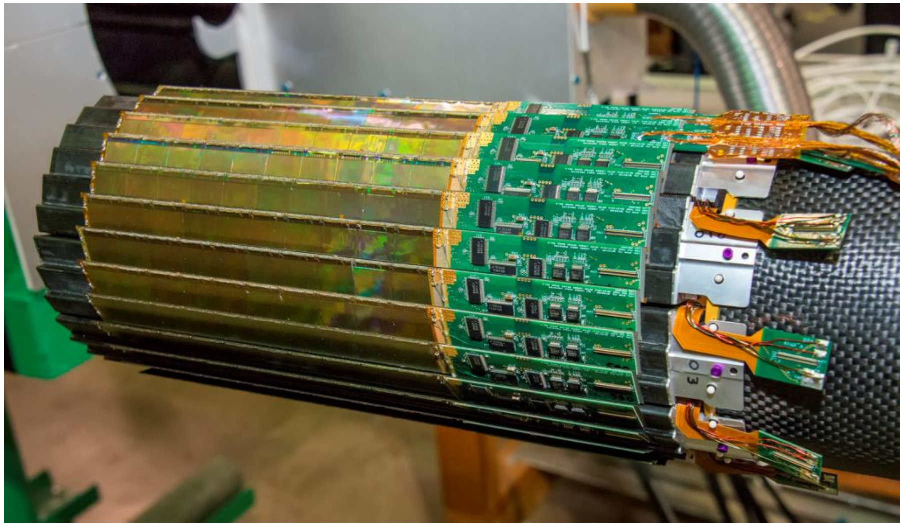
Sector and Detector Half Construction



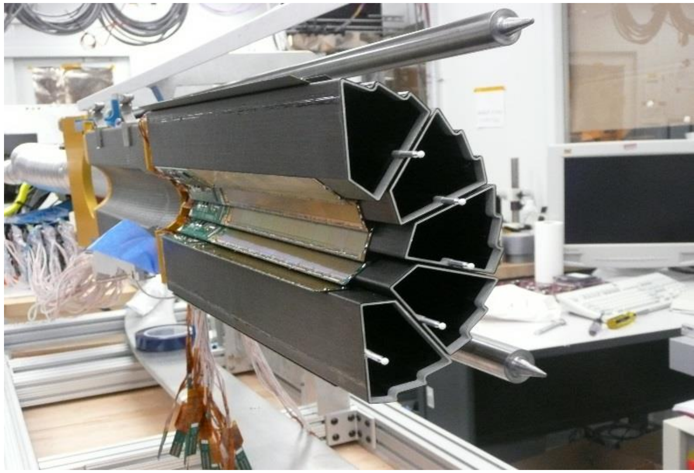
Sector assembly fixture

Sector in the metrology setup

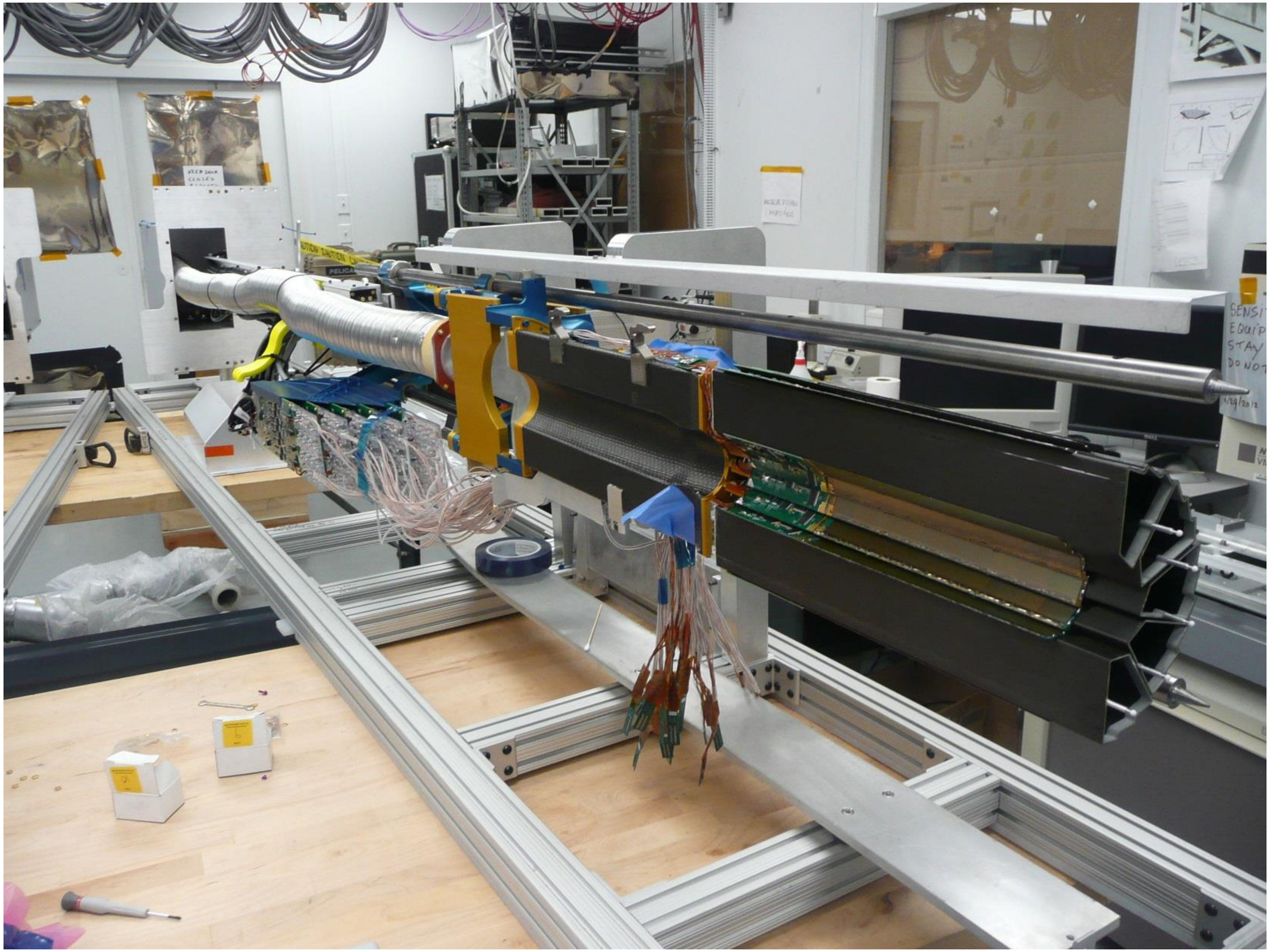




A detector half



Detector Installation: Clean room Tests



Beginning Installation

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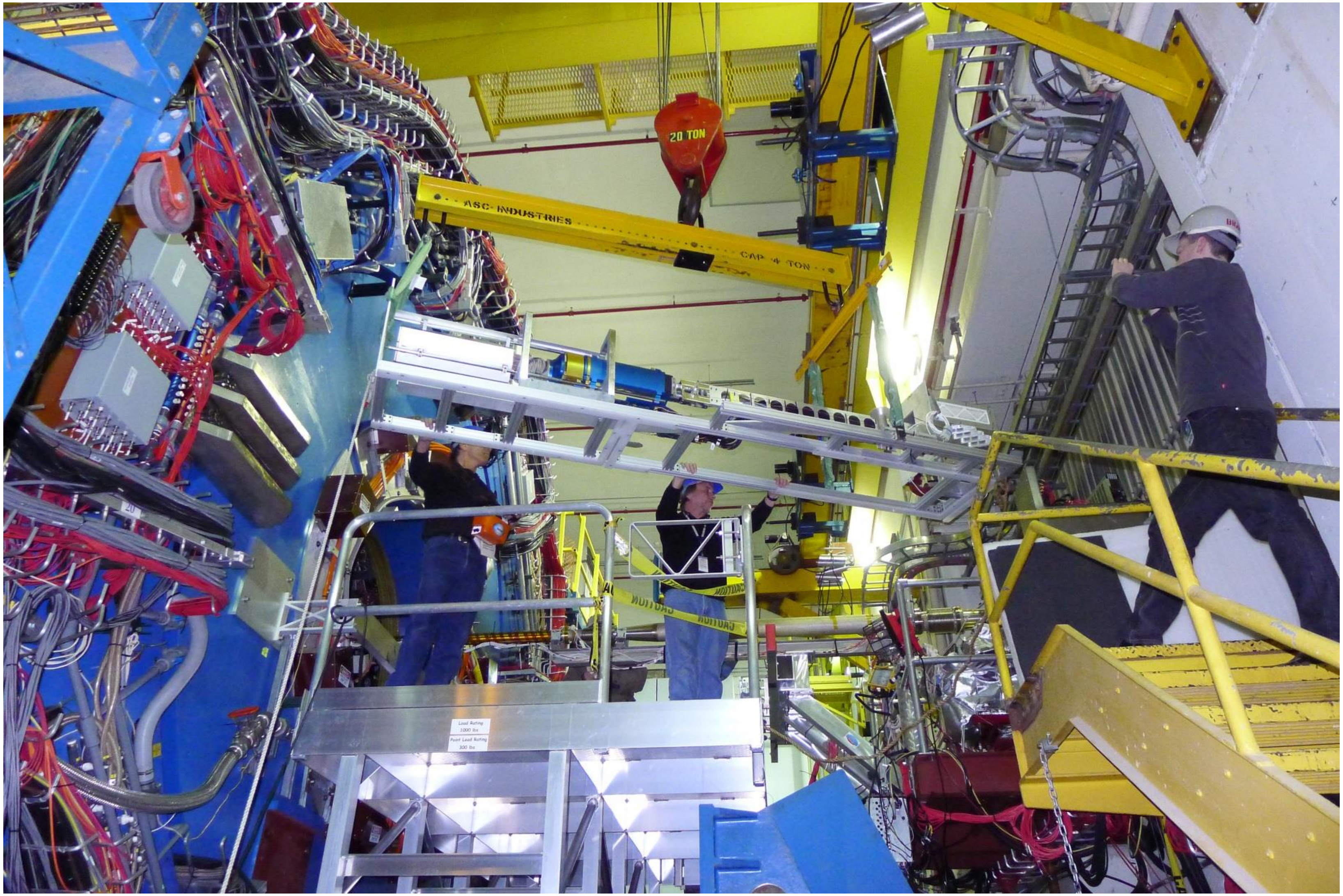
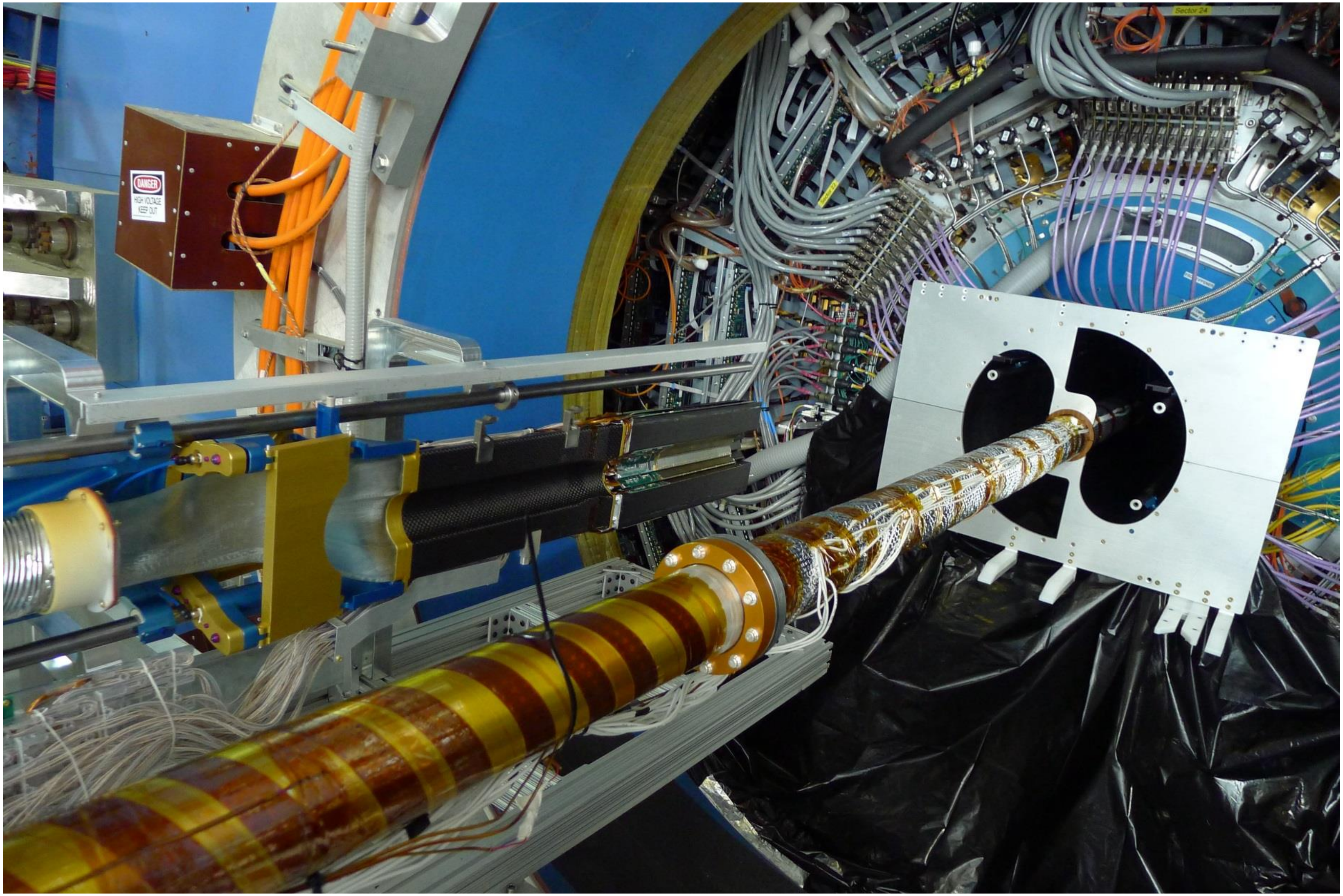
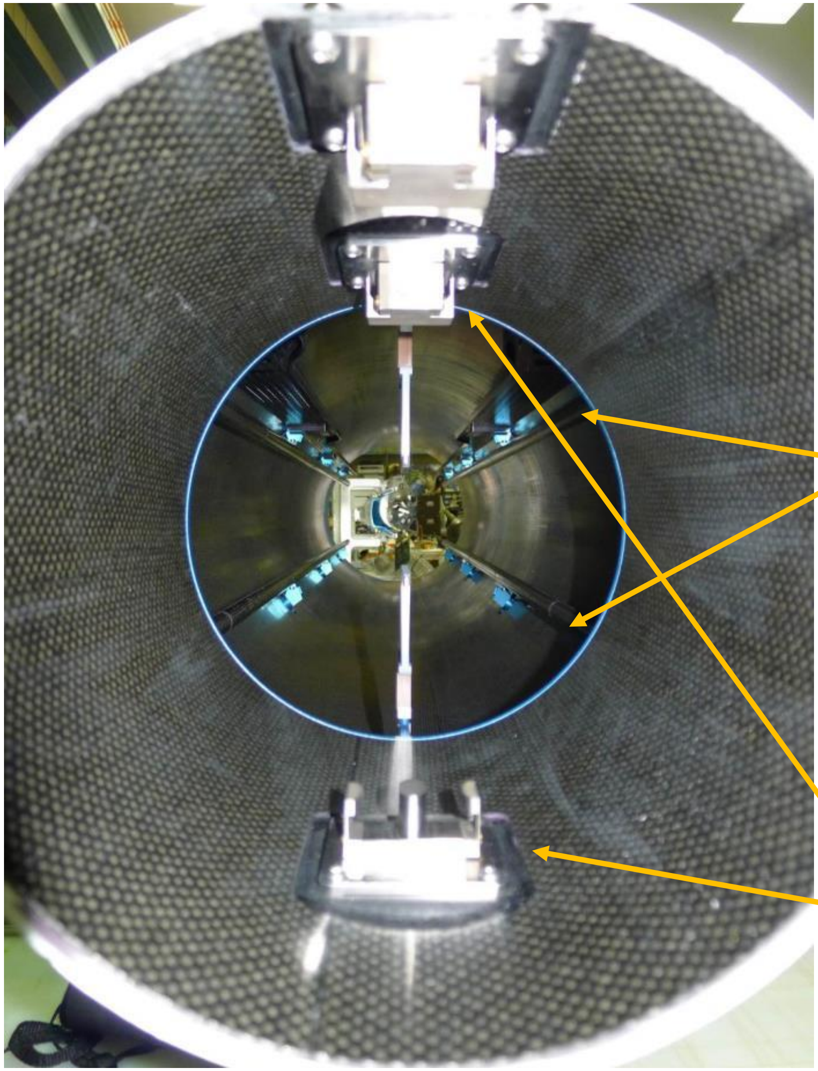


Detector Installation: Insertion into STAR



Unique Mechanical Design

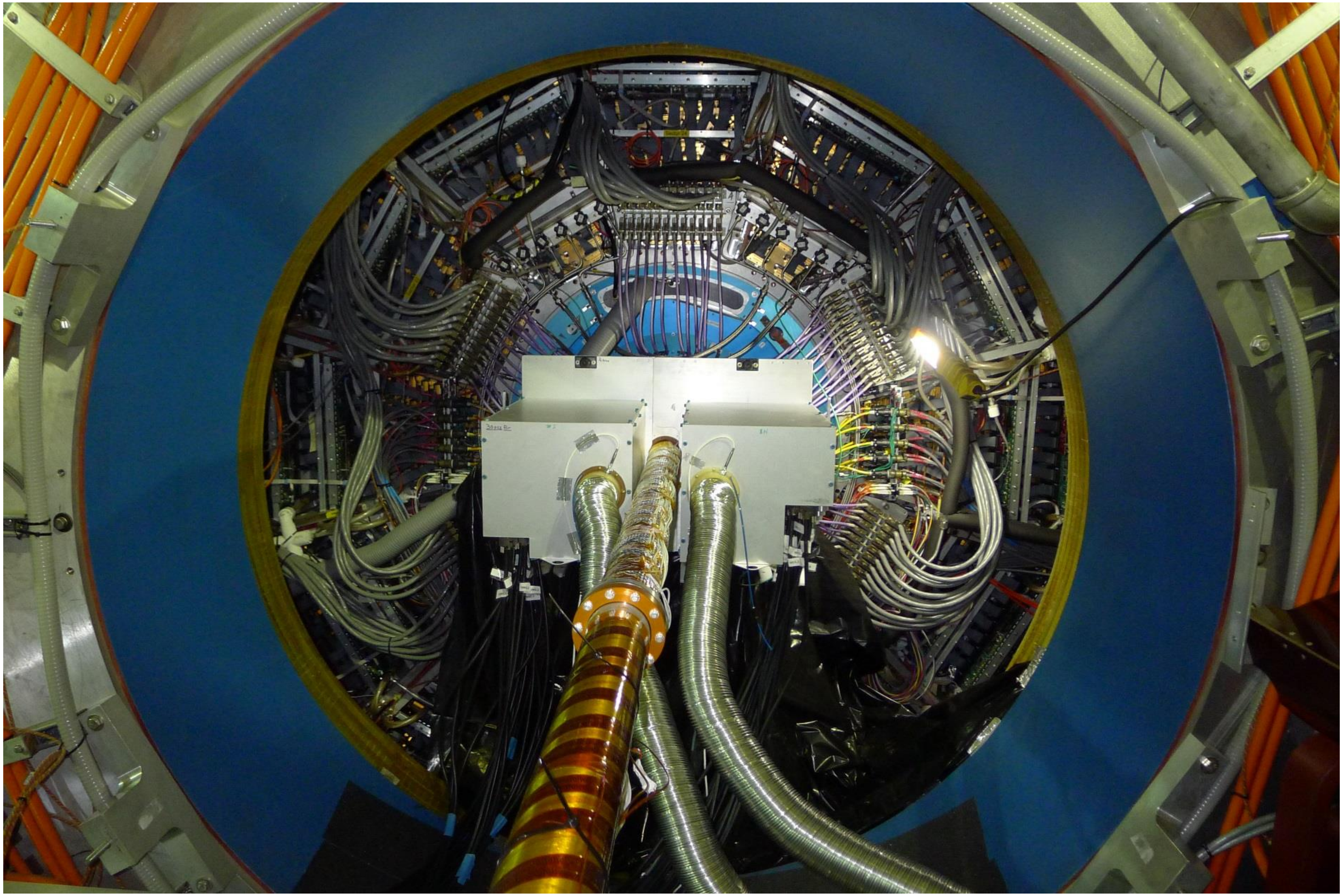


View from Interaction point:

Detector is inserted along Carbon fiber rails

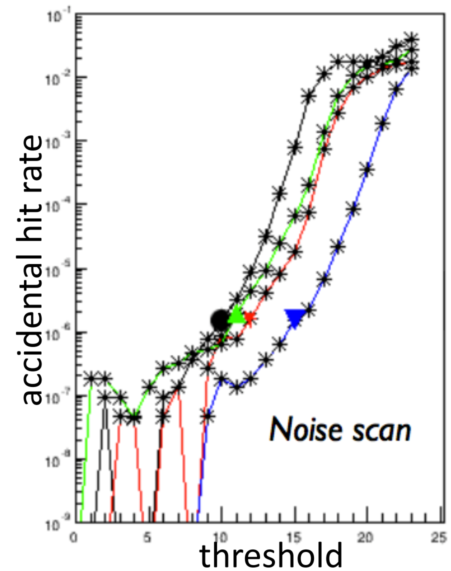
Detector locks into place on Kinematic mounts mounted to support cylinder

After 2 days: PXL installed, cabled & operational

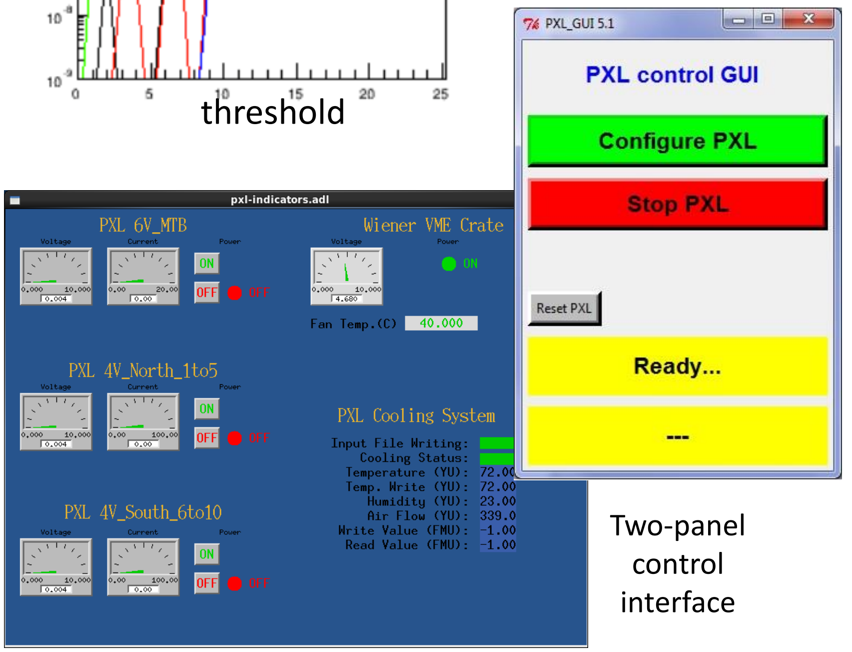


PXL Run Status

- PXL was installed in Jan 2014 with all 400 sensors working, <2k bad pixels out of 356M
- 38 ladders with Cu FlexPC, 2 inner ladders with Al FlexPC
- Noise rates were tuned for ~1-2 x 10^{-6} per sensor for most sensors
- PXL readout through DAQ tested up to 3kHz, typically ~1 kHz during 200 GeV/c Au-Au run with ~120MB/s, < 5% dead time
- Routine operation fully scripted with minimal need for expert intervention



- PXL+IST were included in cosmic-ray triggers before Au-Au runs for alignment
- PXL+IST were used only intermittently in the 15 GeV/c Au+Au run
- PXL+IST were operated since the beginning of the 200 GeV/c Au+Au run



Two-panel control interface

Preliminary Alignment with Cosmics

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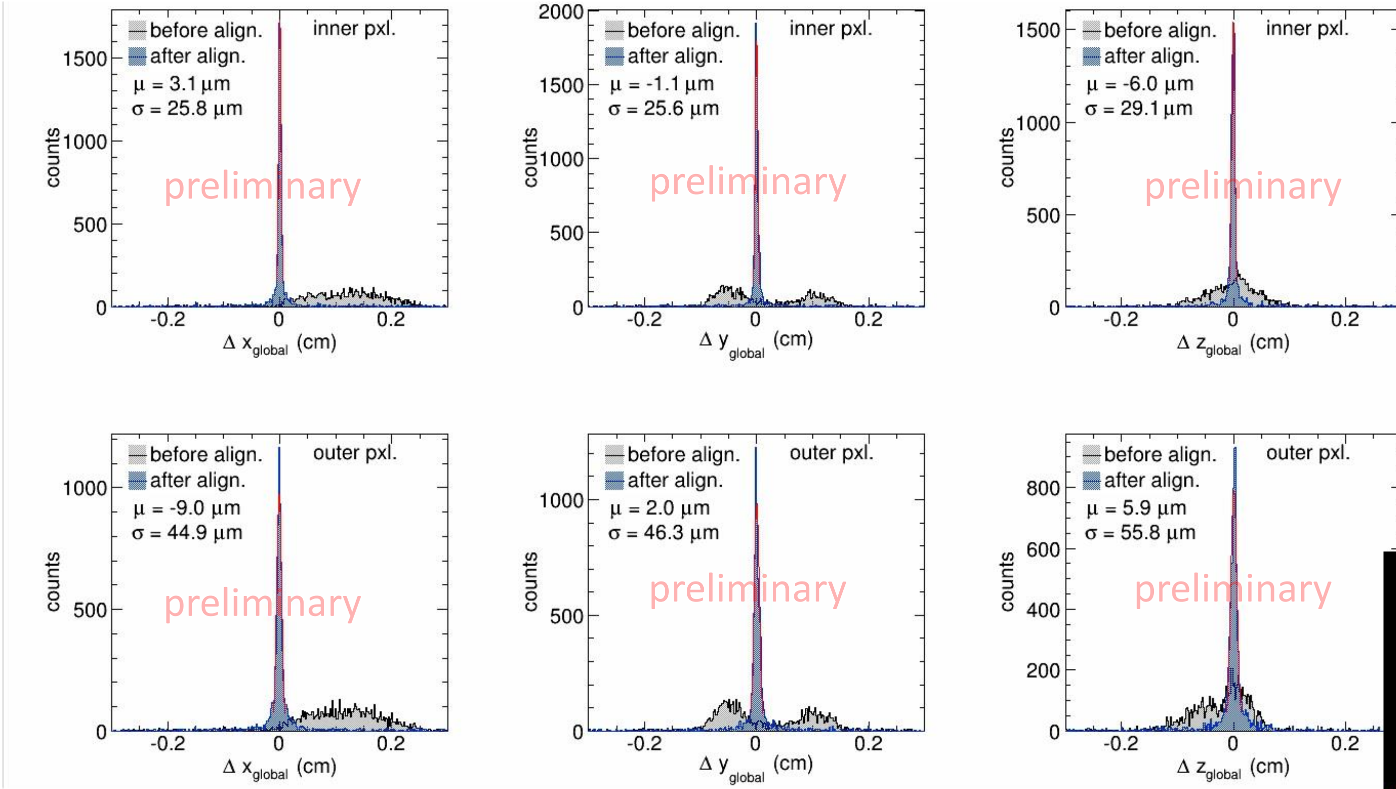
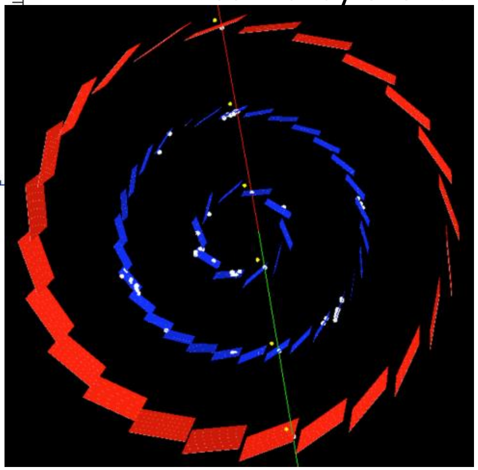
PXL hit residual distributions before and after PXL half to half alignment (analysis by A. Schmah)



Inner layer

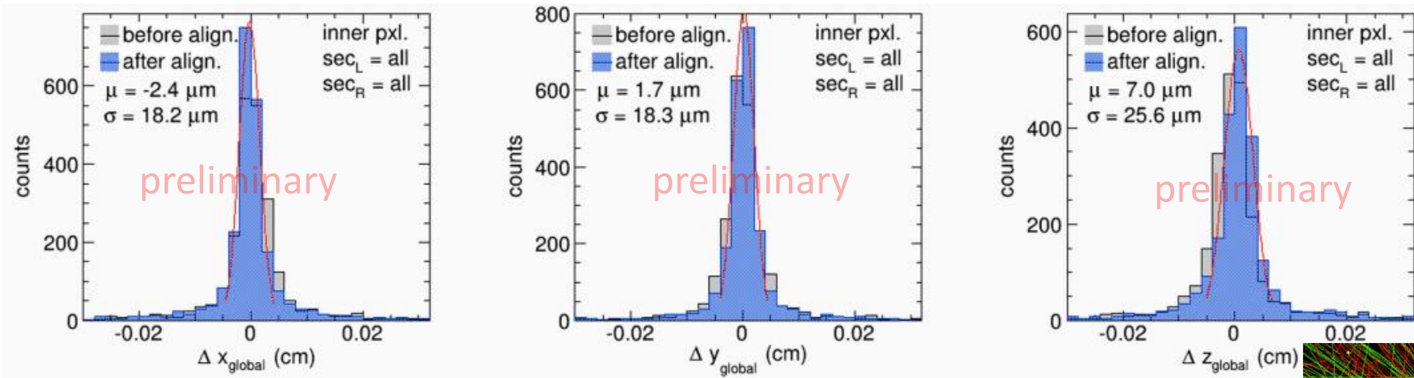
Outer layer

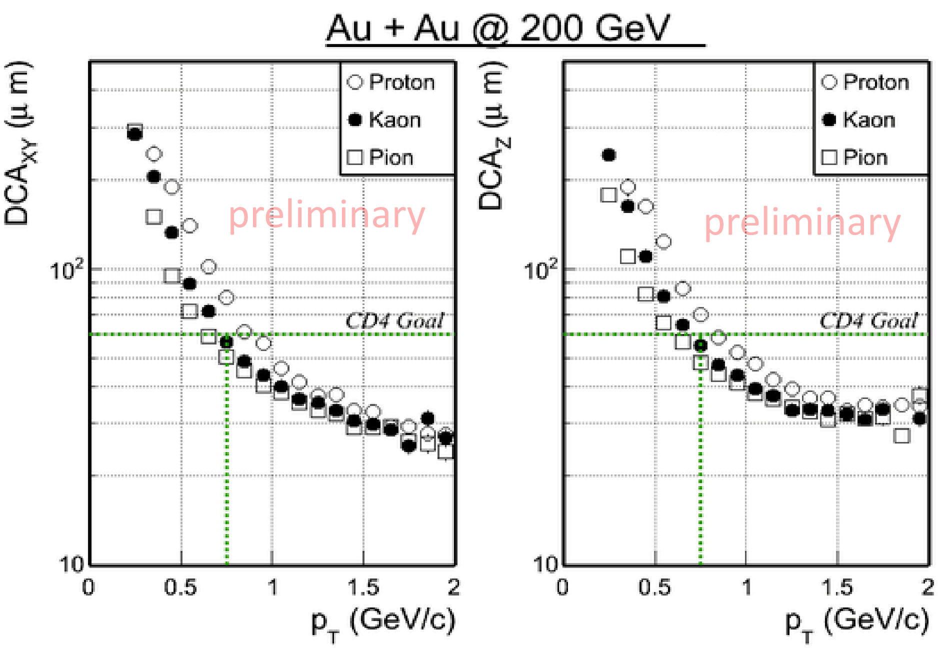
Cosmic ray event



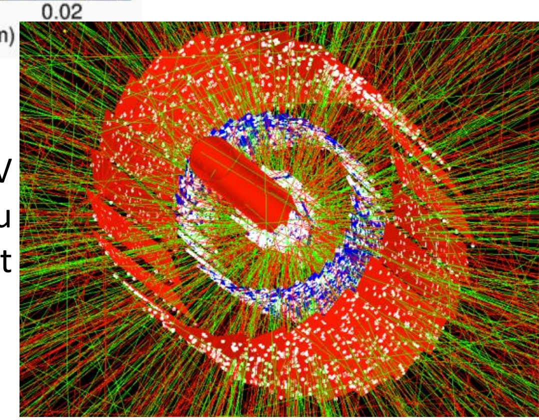
Consistent with expectations for alignment and momentum of muons

Hit Residuals and Track DCA





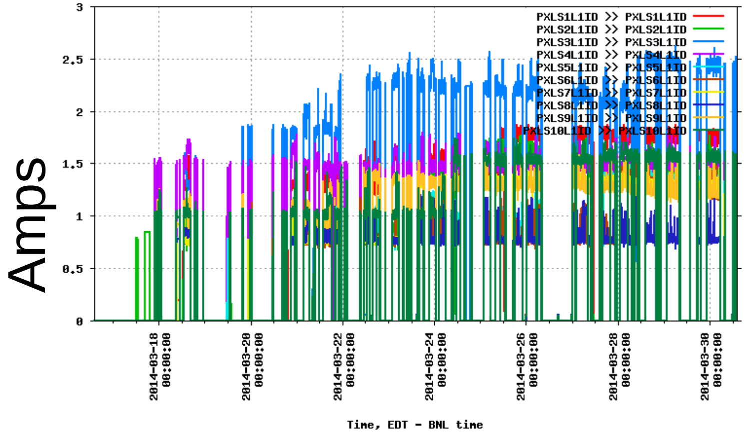
200 GeV Au+Au event



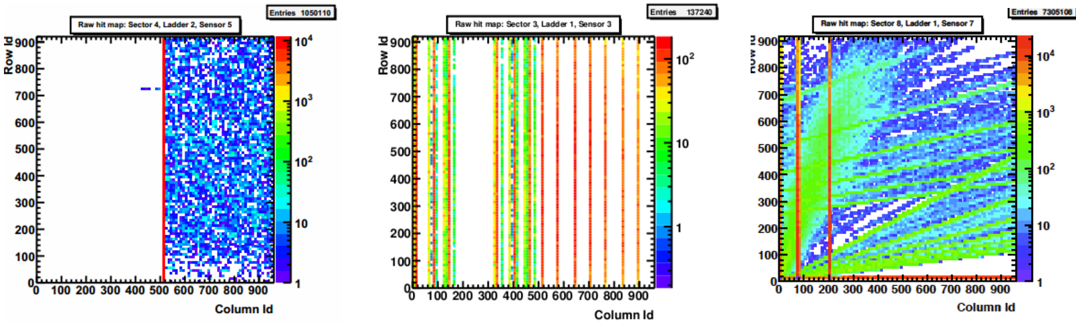
- PXL hit residuals (for cosmics) after sector alignment < 25 μm
- DCA resolution for TPC tracks with 1 IST + 2 PXL hits ~ 30 μm at high p_T (better alignment still in progress will improve these results)
- CD-4 requirement for DCA resolution: 60 μm for kaons with p_T = 750 MeV/c

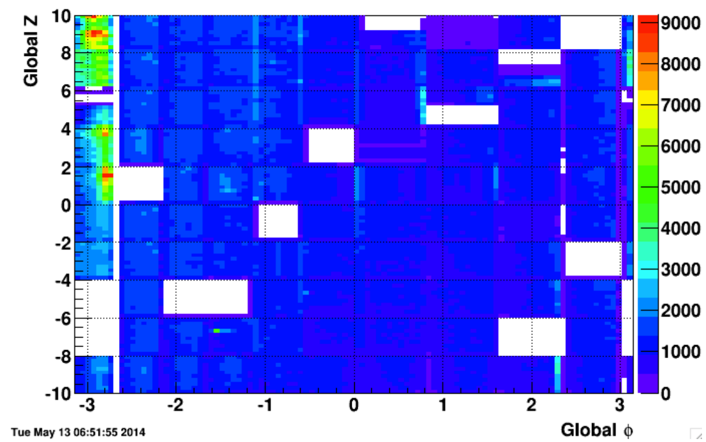
PXL Radiation Damage

Digital current on the inner ladders during initial period of 200 GeV/c Au+Au Run



Sensor damage examples



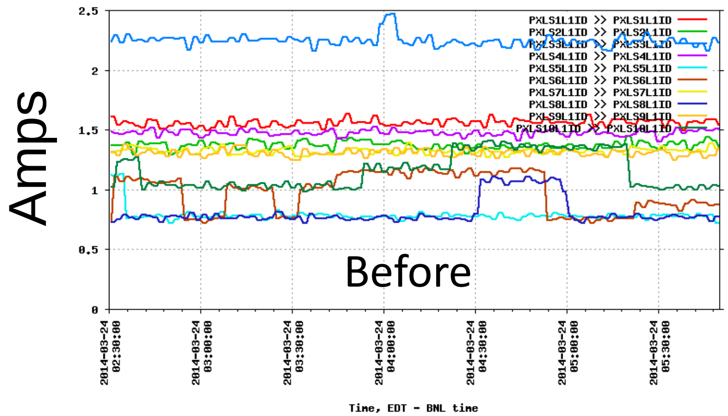


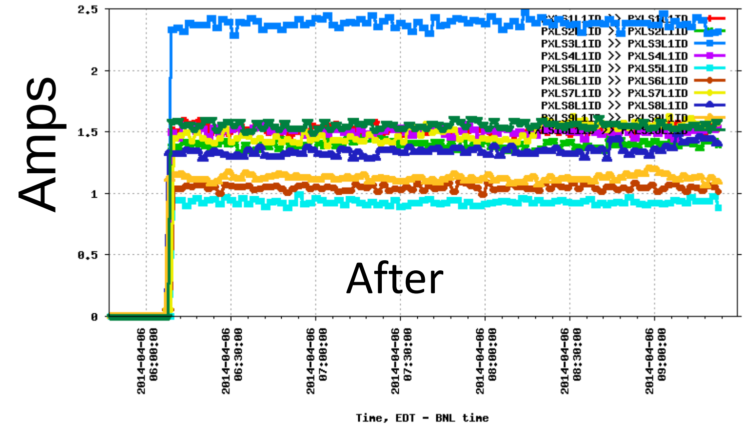
Inner Layer: 14% damage

(Outer layer: 1% damage)

- First sensor damage observed in last week of 15 GeV running after several beam loss events; damage continued into 200 GeV run
- PXL sensor damage appears to be radiation related damage possibly due to latch-up events in thinned sensors and takes on many forms: increased digital current, loss of or damaged columns, damaged JTAG registers, loss of full or partial sub-arrays, etc. (mostly in inner ladders)

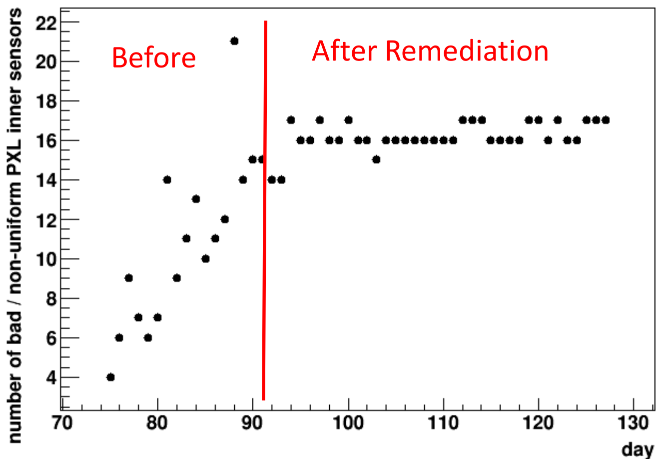
Damage and Remediation





- Initially, digital latchup thresholds were set to 400mA above operational current, allowing large current excursions

“Bad” inner sensors vs time

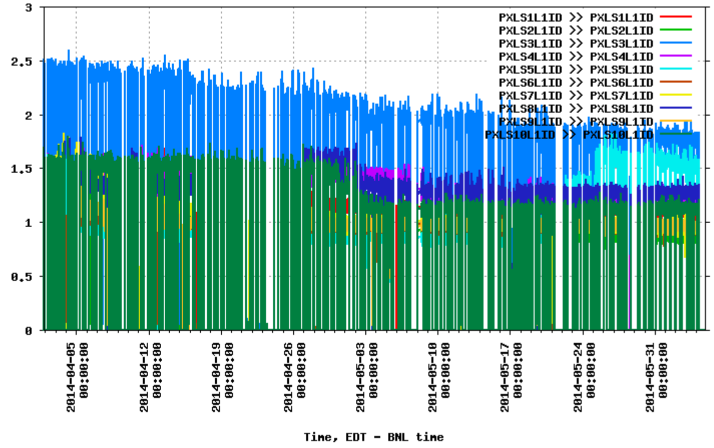


Remediation:

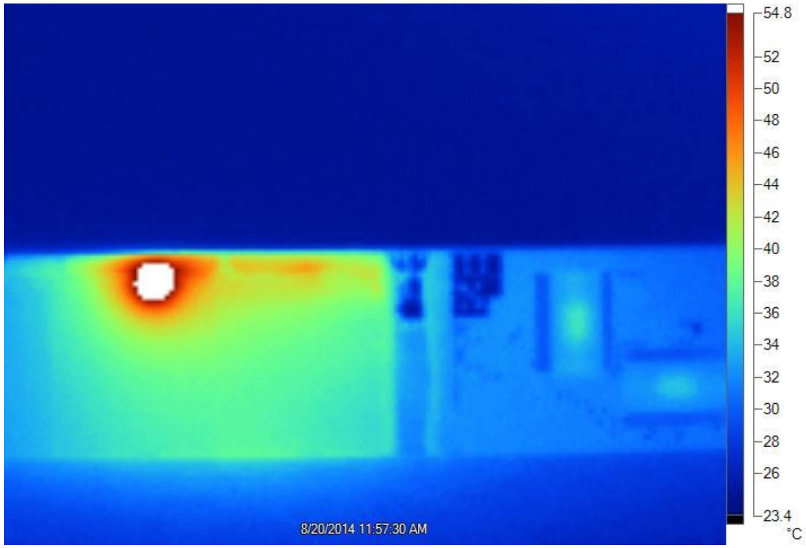
- PXL and IST are only turned on when collision rate < 55 kHz
- Cycle digital power and reload configuration automatically every 15 minutes
- Latchup thresholds now 120 mA above measured operational current for each ladder

Damage and Remediation (cont.)

Digital current on the inner ladders after implementing remediation



- Trend of current in inner ladders over time (~2 months) after operational optimizations.
- Note that this requires continuous adjustment of both LU current threshold and voltage supplied to each ladder.



Post run IR picture showing a hot spot in digital section of a sensor. These hot spots are present on all ladders with increased current draw. Testing is still in progress.

Conclusion and Outlook

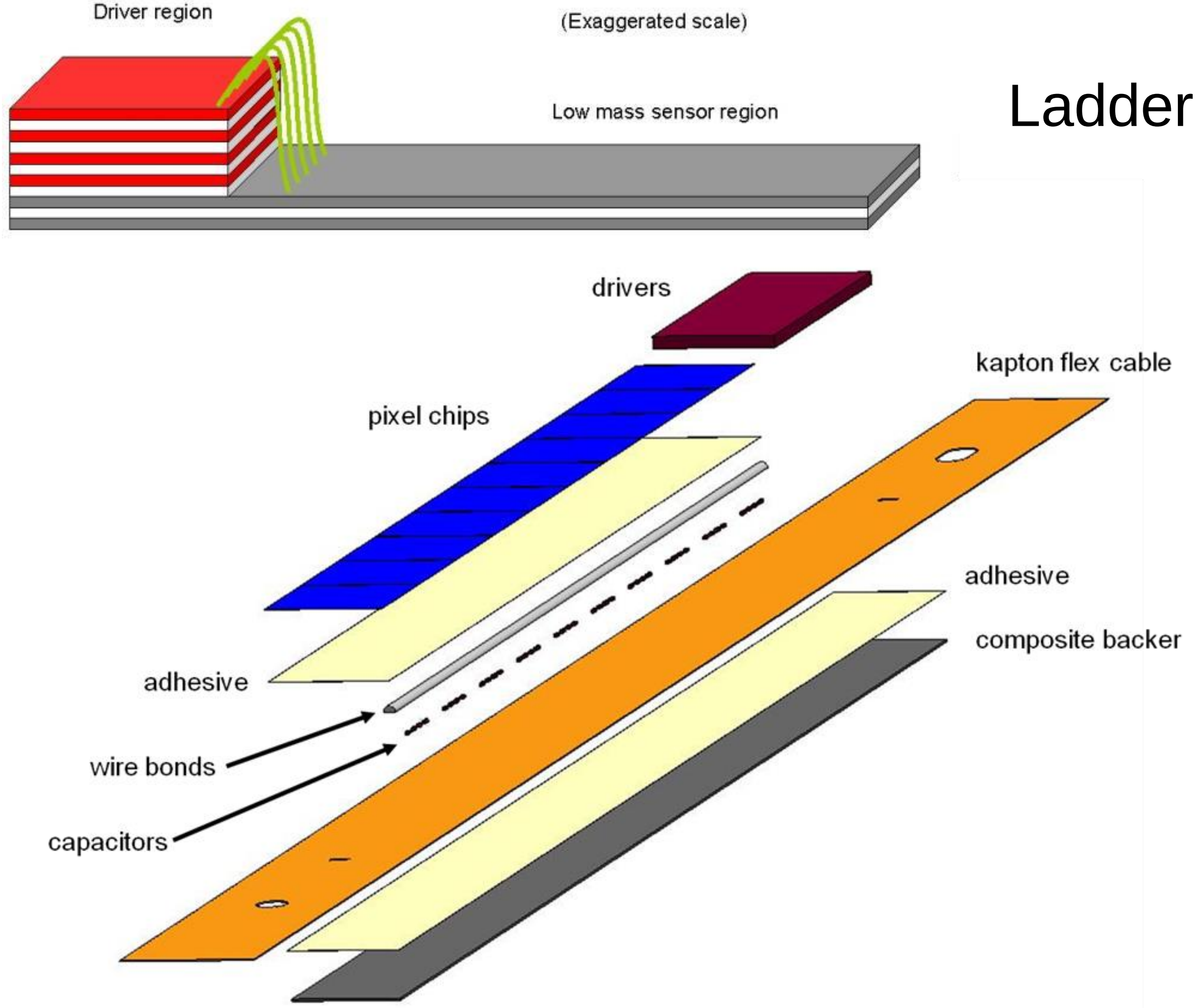
STAR HFT

- STAR Heavy Flavor Tracker installed, successfully integrated into STAR and commissioned for the 2014 Au+Au RHIC run
- State-of-the-art MAPS technology is used for the first time in a collider experiment for a vertex detector
- ~1.2 Billion (200 GeV Au+Au) events were recorded to enable or enhance many open heavy flavor measurements; 200 GeV p+p and more Au+Au data will be taken in RHIC Runs 15 and 16
- The (preliminary) DCA pointing resolution performance of the installed detector appears to be as expected and meets the design goals; analysis is still ongoing and improving
- Sensor damage related to radiation is observed. It appears, however, that we are able to reduce the rate of damage to the PXL sensors with our current operational methods
- We expect to be able to deploy the second detector (which includes Al FlexPCs on the inner ladders) for the next run and replace ladders with damaged sensors on the existing detector
- **MAPS as a technology for vertex detectors appears to be working well**

Thank you

Extra slides

Ladder Design



Ladder cable concept

Transverse thickness of first PXL layer

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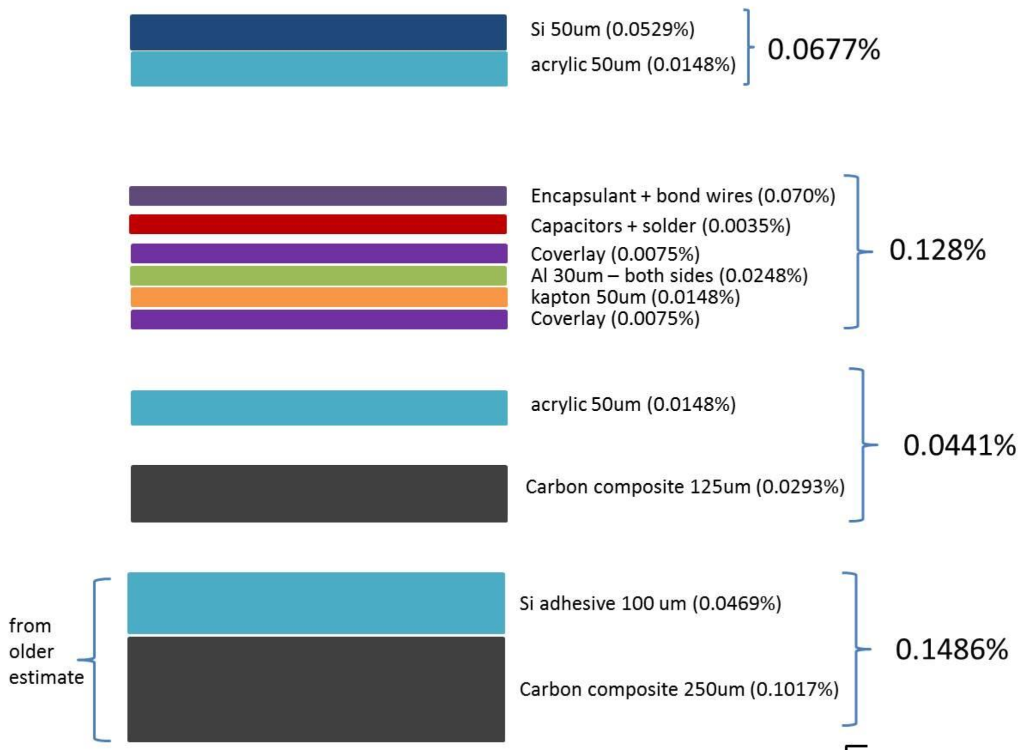
The measurements of an aluminum ladder were performed. In the active area, the breakdown of radiation length is shown below.

Radiation length in low mass area



NOTE: Does not include sector tube side walls

The copper conductor PCB version increases the radiation length of the conductor to 0.129% X_0 (corrected for the thinner copper layer). This increases the overall radiation length of the copper based inner ladders to 0.492% X_0.

Total = 0.388%

Post Au-Au run testing

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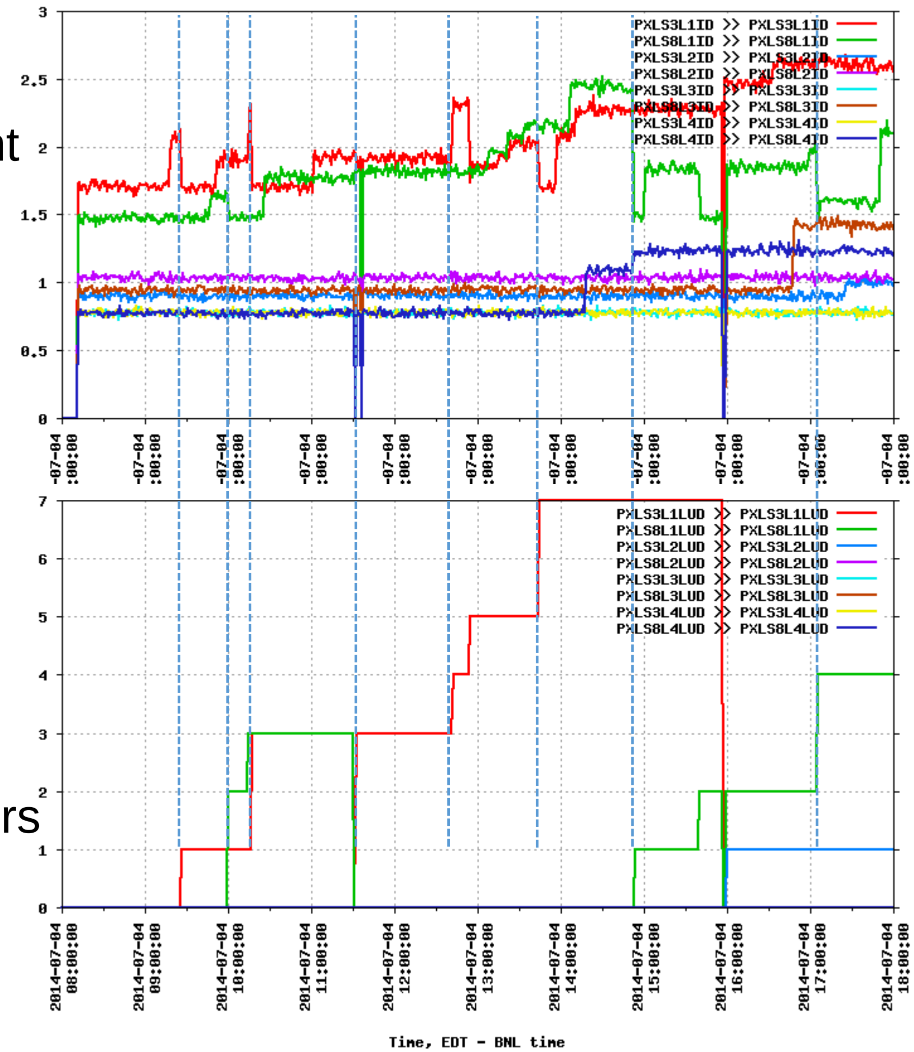
Current

LU Counters



Set LU thresholds to 500mA above operating current and run for ~8 hours with ^{3}He-Au. (sectors 3 and 8 to allow for cosmic ray data after testing)

Disable periodic reset.

Test had the potential to be destructive so not attempted during data taking run.

Current increases and some resets observed in inner and outer ladders. (some resets take multiple attempts before ladder operation is re-established)

All currents returned to pre-test levels after power cycling the system.

Sampled every few minutes, some increases were missed.

Post-run testing observations

- Non-reset current increases are observed with high LU thresholds in ^{3}He-Au running (~1/2 multiplicity).
- Some increases are reset, some persist and do not trigger reset.
- This behavior is attributed to SEU in some part of the sensor, but this is not understood.
- No permanent damage was observed (the sensors returned to their pre-test operating current and maintained functionality), this is consistent with the previously observed rate of ~1 sensor/day (of 100 in the inner layer) permanently damaged during the Au-Au run.
- This behavior will be examined further in LU testing in October.
- JTAG testing – 24 sensors failed JTAG register testing. ~80% of sensors with JTAG errors are in the inner layer.
- Measured noise in sensors (1 sector, analysis still in progress) appears to be unchanged from beginning of run. (no significant ionizing radiation dose?)

Possible Mechanisms

STAR HFT

- Non-ionizing (Neutron) damage? – Dislocation of atoms in the matrix generally results in permanent damage to silicon. This is consistent with what we observe. In discussions with Matt Durham who worked on the Phenix FVTX detector, he indicated that the beam tune into Phenix had some component of scraping against a magnet or beam pipe surface that caused spallation neutron based damage in their detector and that the neutron rate was nearly 3 orders of magnitude above what was calculated. In our case, we have no information about the neutron flux at low radii from the beamline.
- Ionizing radiation damage? – The primary source of ionizing radiation damage is expected to come from the transit of MIPs through the sensors. This is expected to show up in hits registered in sensor pixels. The occupancy of charged tracks is approximately what was projected in the simulations (~300 hits per frame on the inner ladders and ~100 hits per frame in the outer ladders). The likelihood of normal beam activities causing the damage observed is judged to be low. There have been, however, a significant number of non-standard events during this run. Particularly during the 15 GeV run period.
- LU related damage? – It is possible that LU events could cause damage in the silicon. This would need to be a phenomenon particular to thinned silicon and/or high resistivity epi. We did extensive testing of full thickness sensors at the BASE facility at the 88” cyclotron at LBNL where we exposed sensors to many thousands of LU events to measure the LU LET onset and cross-section.