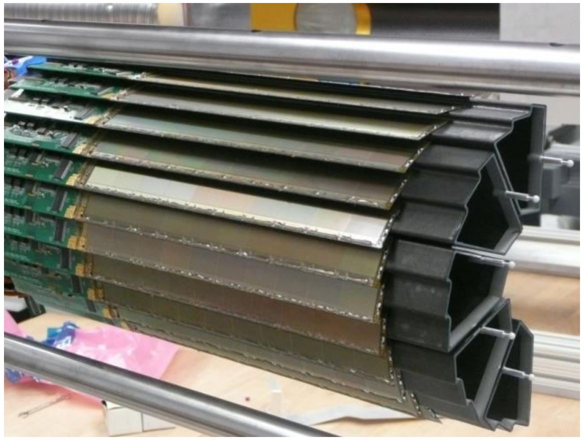
Lessons learned from the STAR PXL detector



HICforFAIR Workshop: Heavy flavor physics with CBM

26 - 28 May 2014   Frankfurt, Germany

Michal Szelezniak   IPHC/(LBNL)

On behalf of:

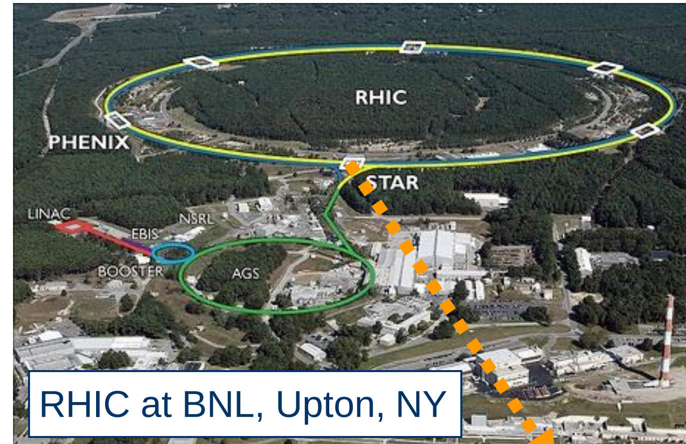
LBNL: *Leo Greiner, Eric Anderssen, Giacomo Contin, Thorsten Stezelberger, Joe Silber, Xiangming Sun, Chinh Vu, Howard Wieman, Sam Woodmansee*

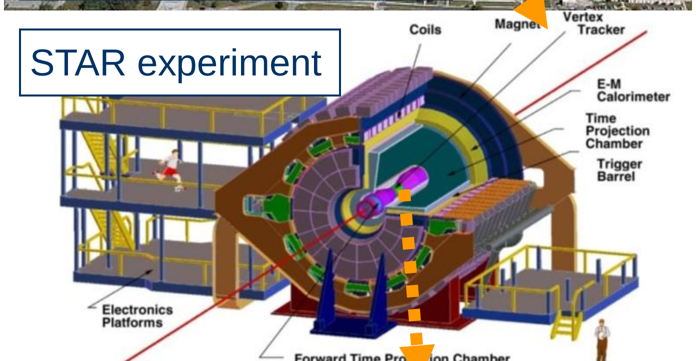
UT at Austin: *Jo Schambach*

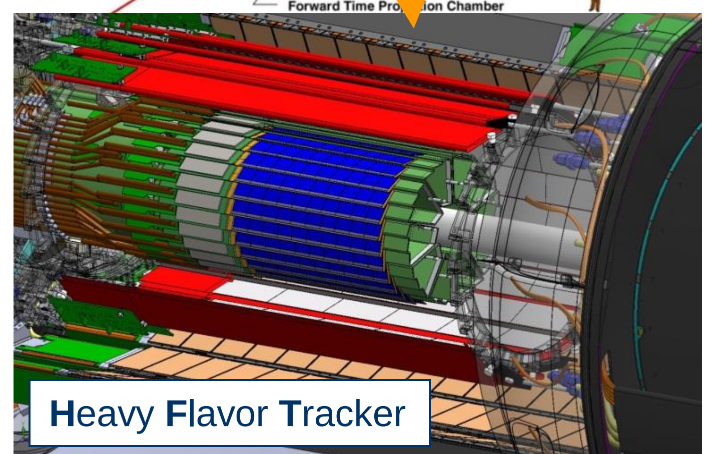
PICSEL group, IPHC, Strasbourg: *Marc Winter et al.*

Outline

- STAR HFT Upgrade
- PXL Detector
  - Characteristics
  - Structure
  - MAPS
  - Readout
- PXL status
  - Installation (January 2014)
  - Preliminary performance
- Lessons Learned
  - Senor testing
  - Construction
  - Engineering run 2013
  - Physics run 2014
- Summary and Outlook

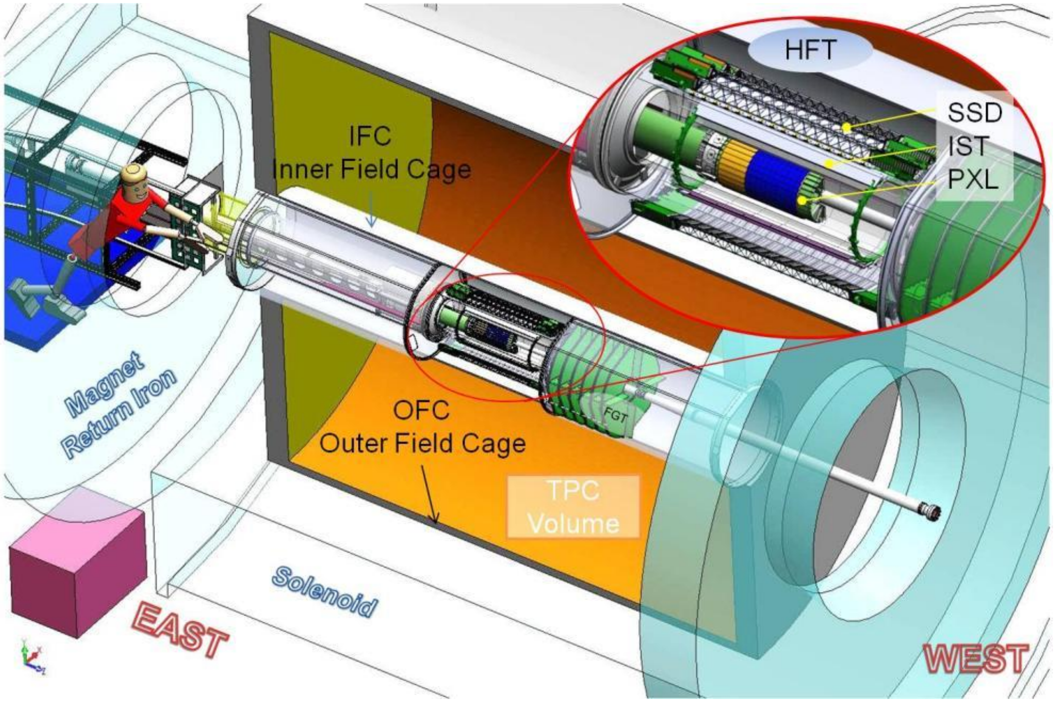






STAR Heavy Flavor Tracker (HFT) Upgrade

- to identify mid rapidity Charm and Beauty mesons and baryons through direct reconstruction and measurement of the displaced vertex with excellent pointing resolution.

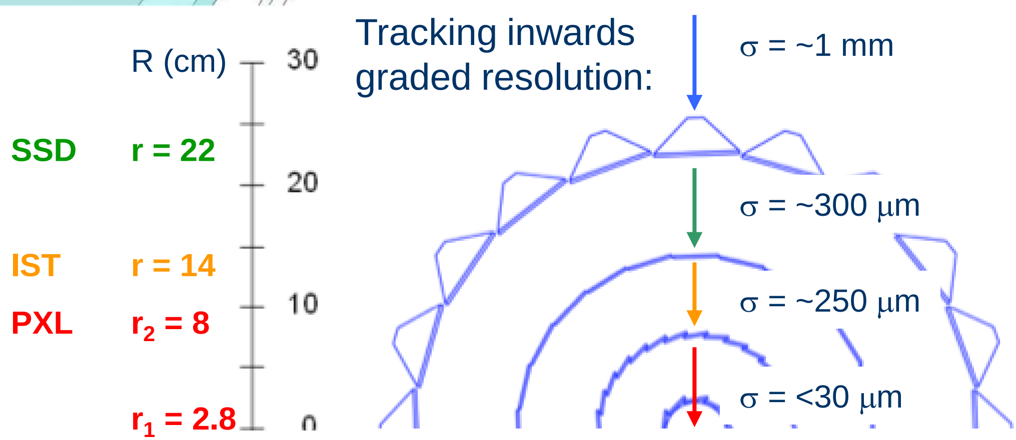


TPC – Time Projection Chamber (main tracking detector in STAR)

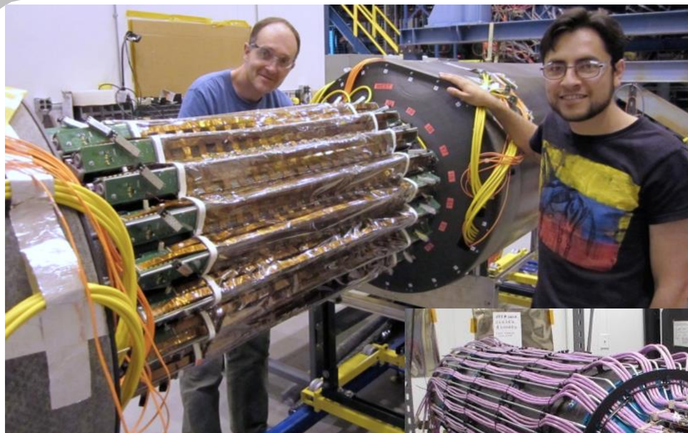
HFT – Heavy Flavor Tracker

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

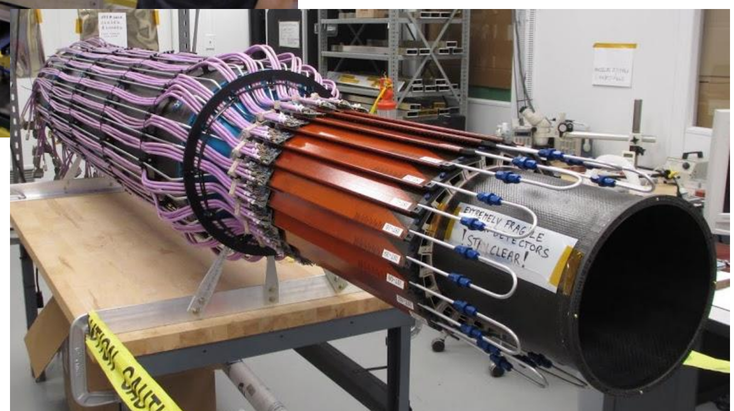
Tracking inwards graded resolution:



HFT subsystems



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



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

- **PXL**
  - MAPS sensors with 20.7 µm pitch
  - Radius: 2.8 and 8 cm

first MAPS based vertex detector at a collider experiment

STAR HFT

PXL Characteristics

DCA Pointing resolution *	$(12 \oplus 24\ \mathrm{GeV}/p{\cdot}c)\ \mu m$
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 (hot spare copy of the detector)	~ 1 day

356 M pixels on ~0.16 m^2 of Silicon

* Pointing resolution is limited by MCS and mechanical stability

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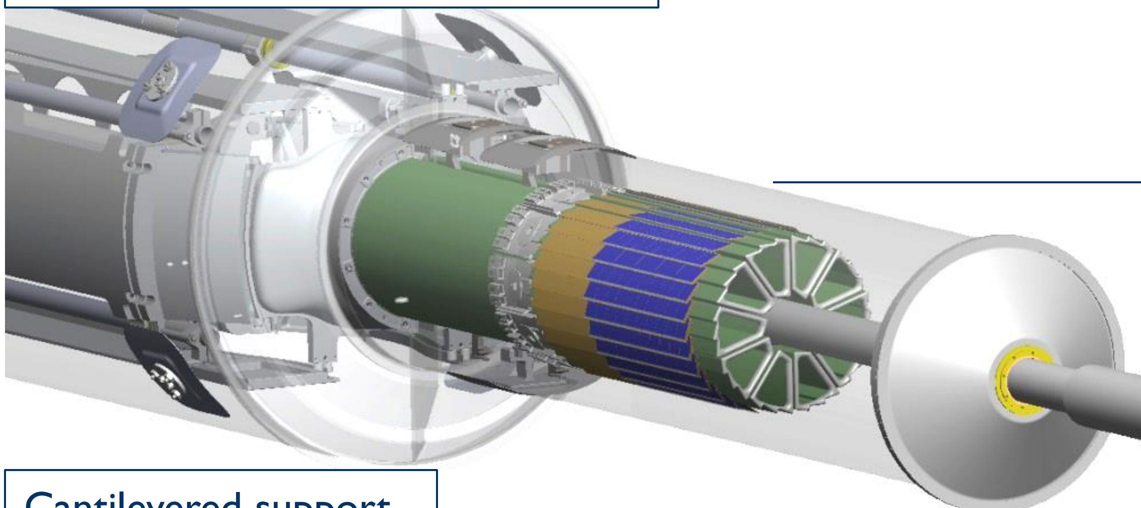
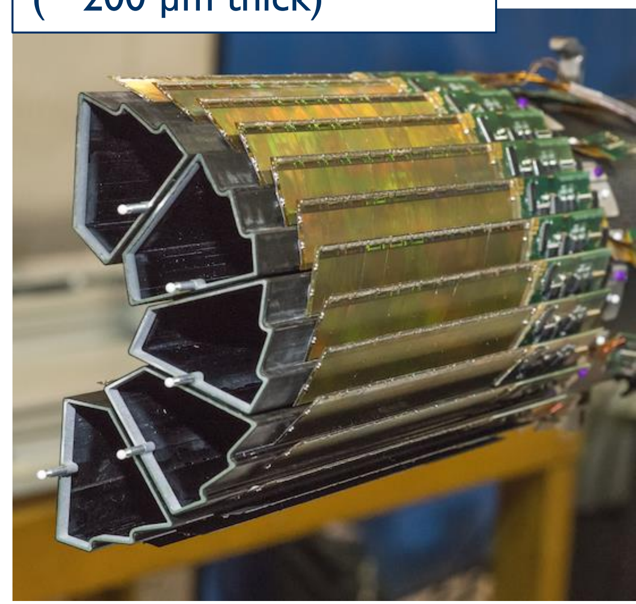
PXL architecture

Mechanical support with kinematic mounts (insertion side)

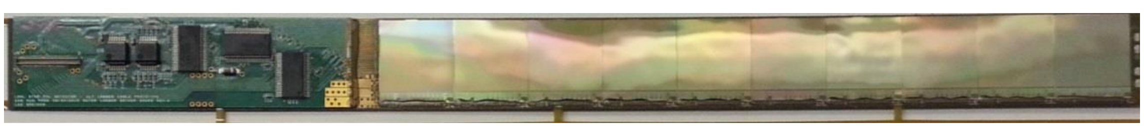


Cantilevered support

carbon fiber sector tubes (~ 200 μm thick)

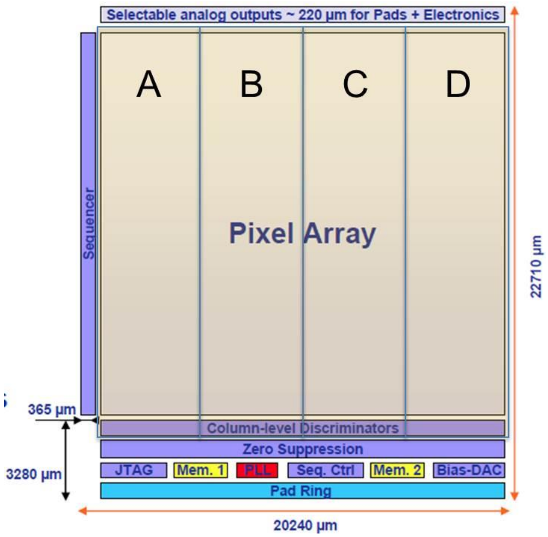


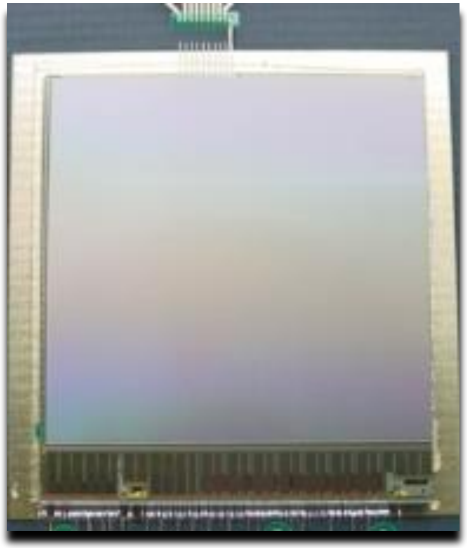
Ladder with 10 MAPS sensors (~ 2×2 cm each)

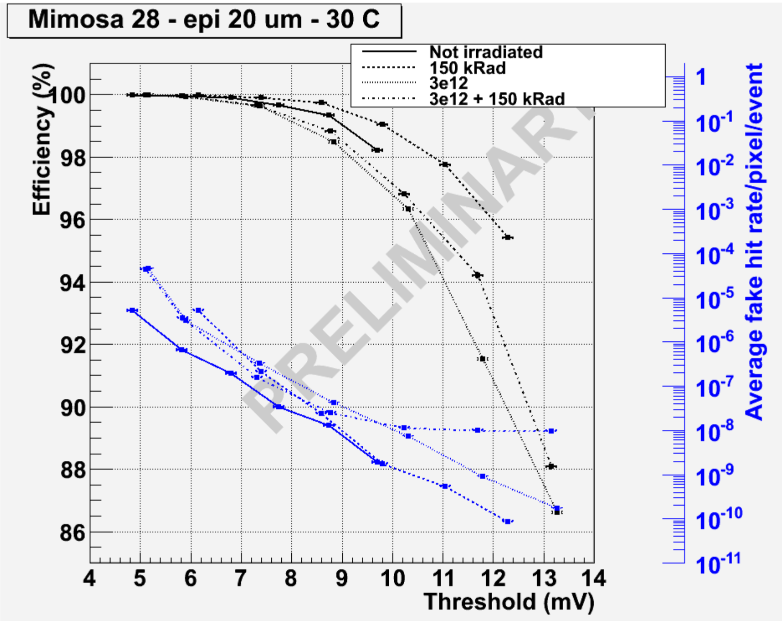


- Insertion from one side
- 10 sectors total
- 5 sectors / half
- 4 ladders / sector

PXL detector Ultimate-2 Sensor







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

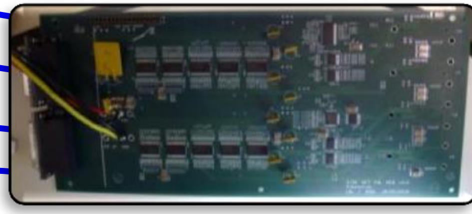
- Reticle size (~ 4 cm²)
  - Pixel pitch 20.7 µm
  - 928 x 960 array
- Power dissipation ~170 mW/cm² @ 3.3V (air cooling)
- Short integration time 185.6 µs
- Sensors thinned to 50 µm

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

PXL Detector Readout Chain

11 m (24 AWG TP)

Clk, config, data

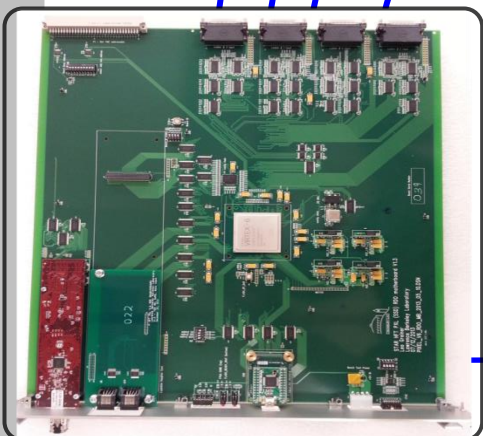


Mass Termination Board
- signal buffering
- latch-up protected power

2 m
(42 AWG TP)

Clk, config, data, power

PXL Sector
- Continuous readout



RDO motherboard
w/ Xilinx Virtex-6 FPGA
- event building

100 m (fiber optic)

PXL built events

DAQ PC with RORC

Trigger,
Slow control,
Configuration,
etc.

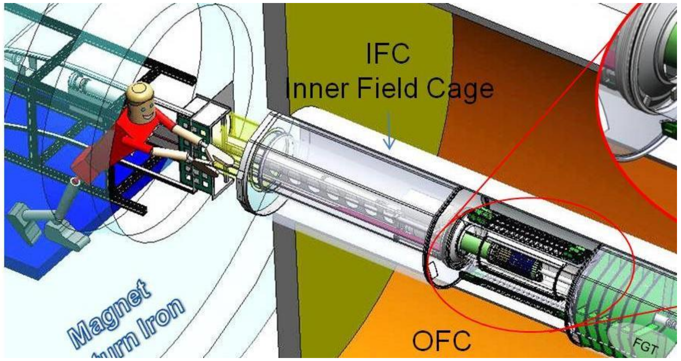
Highly parallel system

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

STAR HFT

PXL insertion

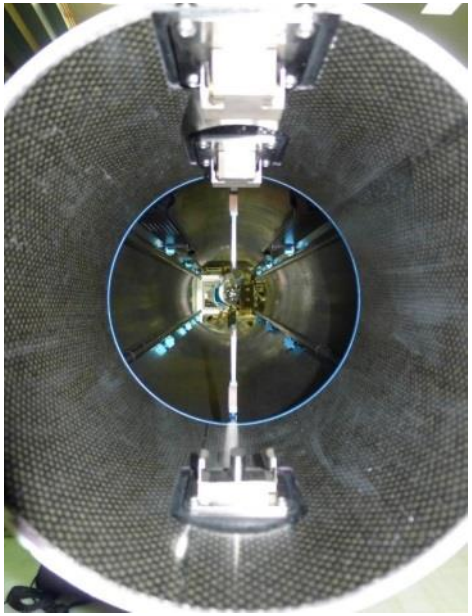
Yes – we push it in by hand



Unique mechanical design:

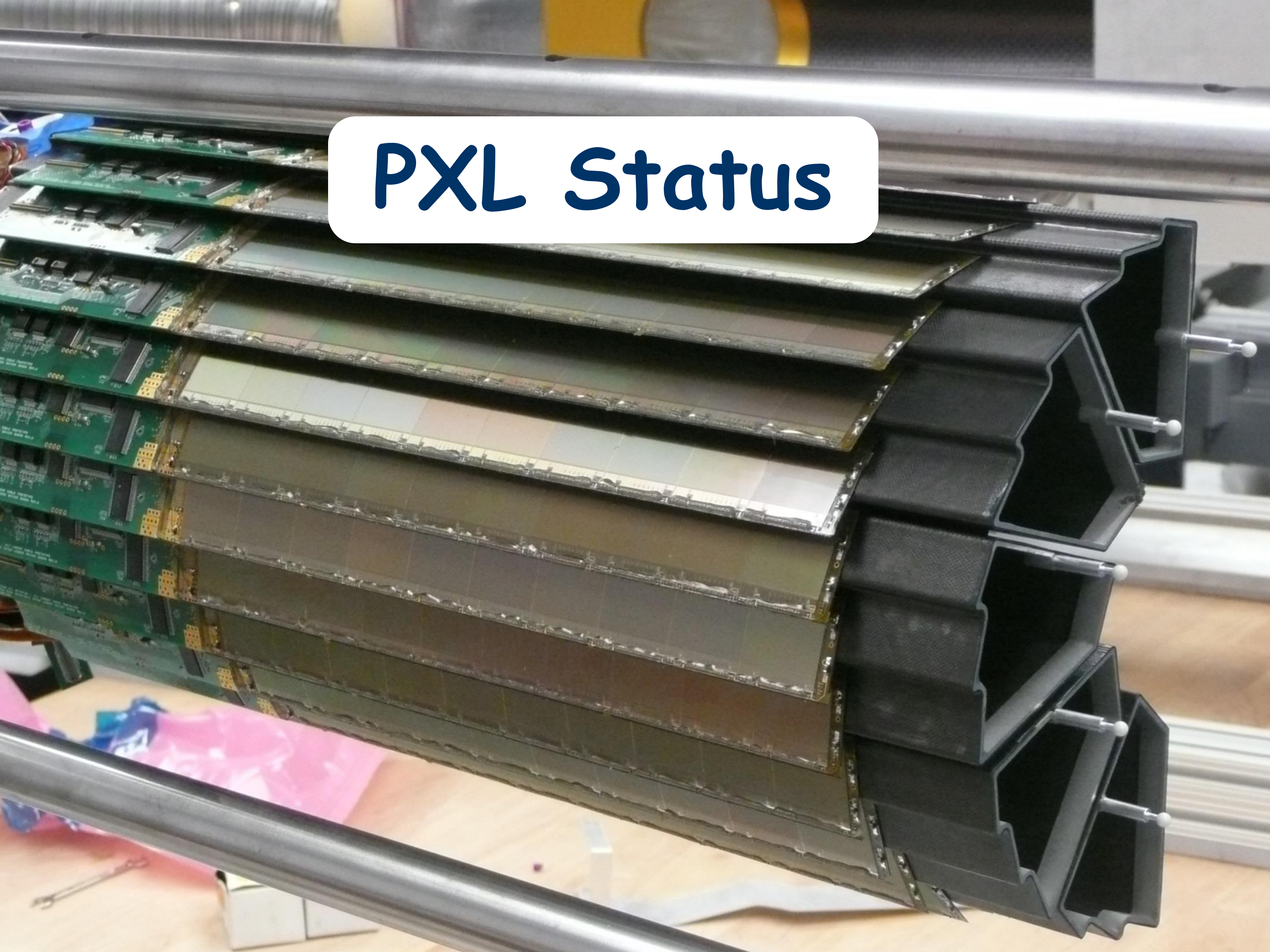
- detector is inserted along rails and locks into a kinematic mount on the insertion end of the detector
- Allows for rapid (1 day) replacement with a characterized spare detector

Kinematic mounts



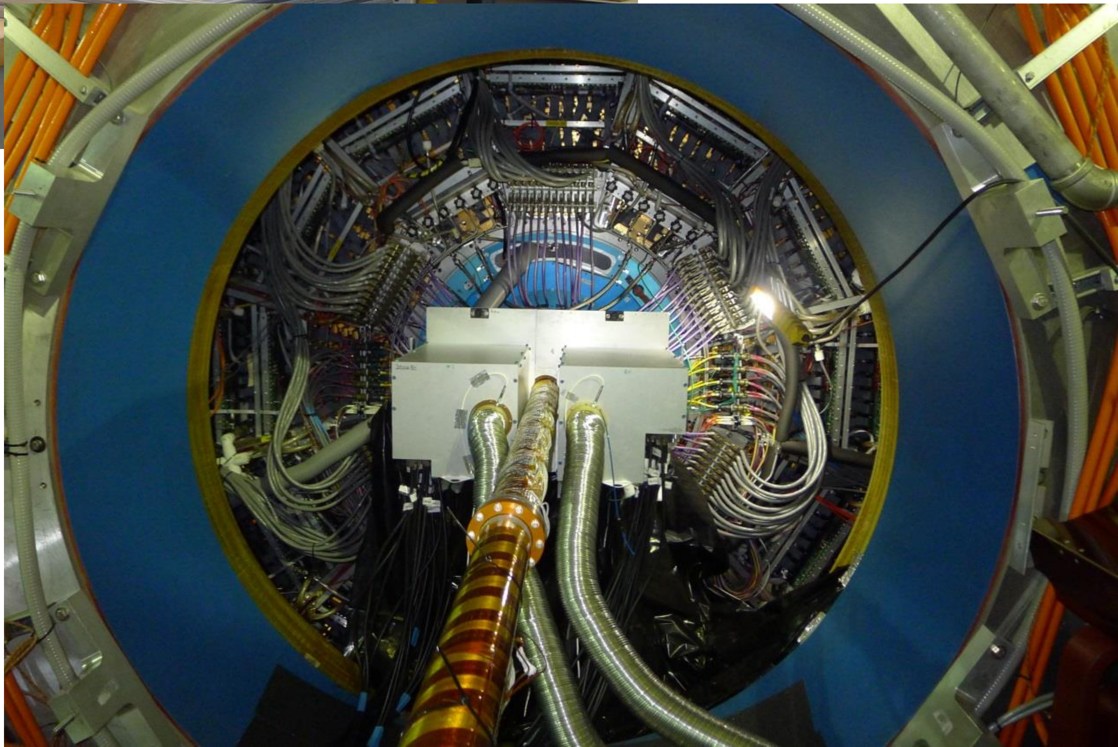
Insertion of PXL detector

PXL Status



Detector Installation

PXL assembled in the STAR clean room @BNL



PXL inserted and cabled into the STAR TPC inner field cage and operational
Total installation time = 2 days

PXL Electronics and operator's GUI

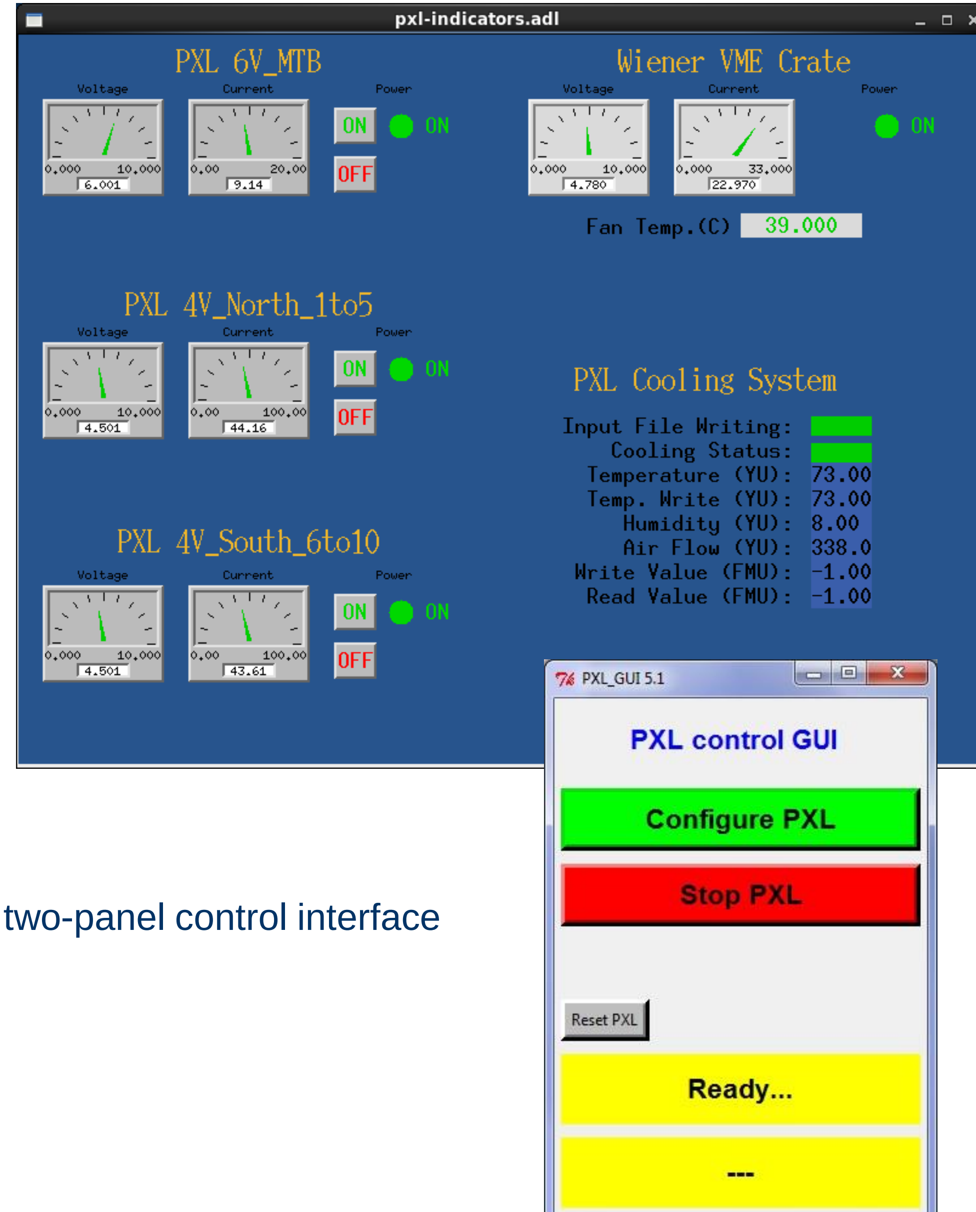
USB hub
USB<->fiber
interlocks

4V South

6V MTBs

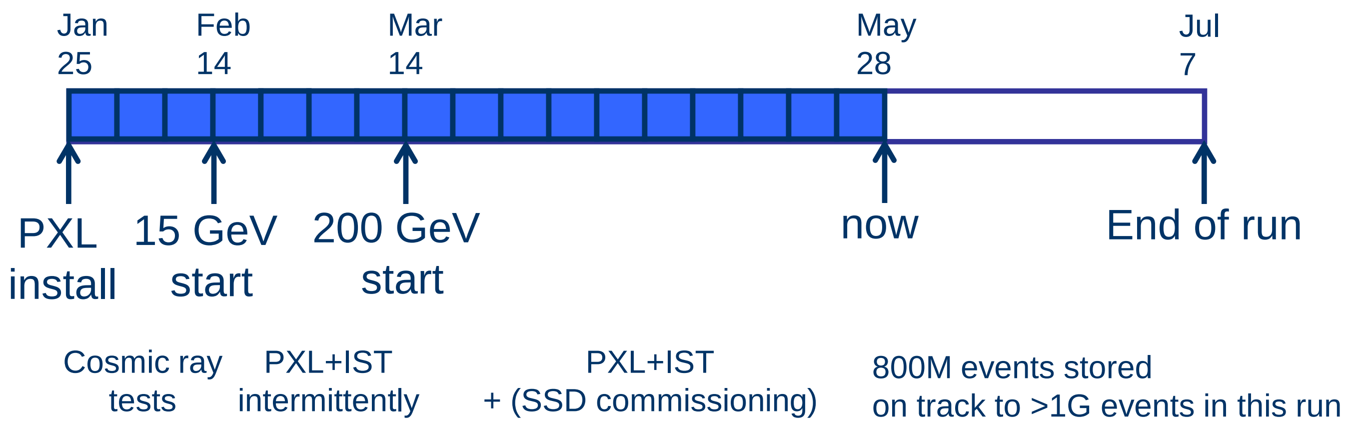
4V North

10 RDO boards
1 Trigger
distribution board



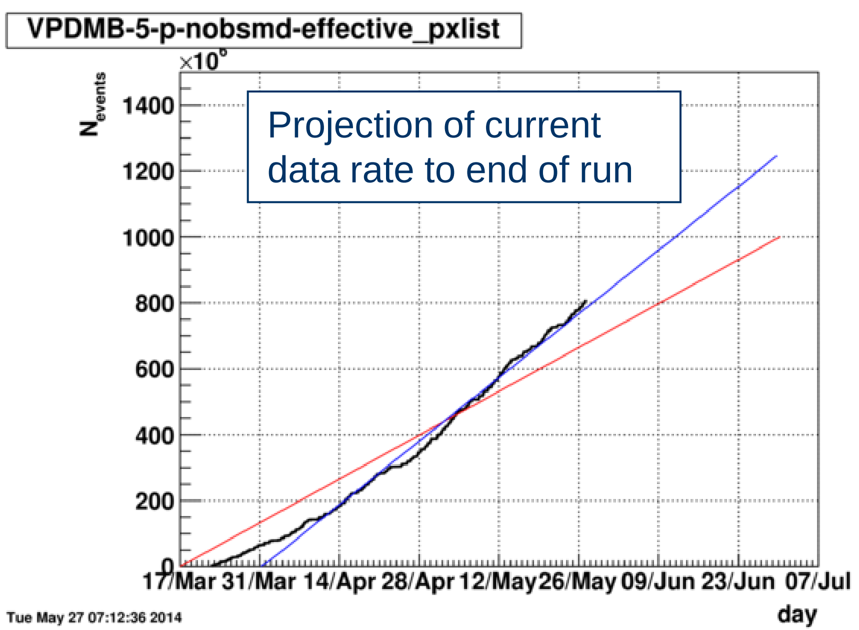
two-panel control interface

PXL Run Status



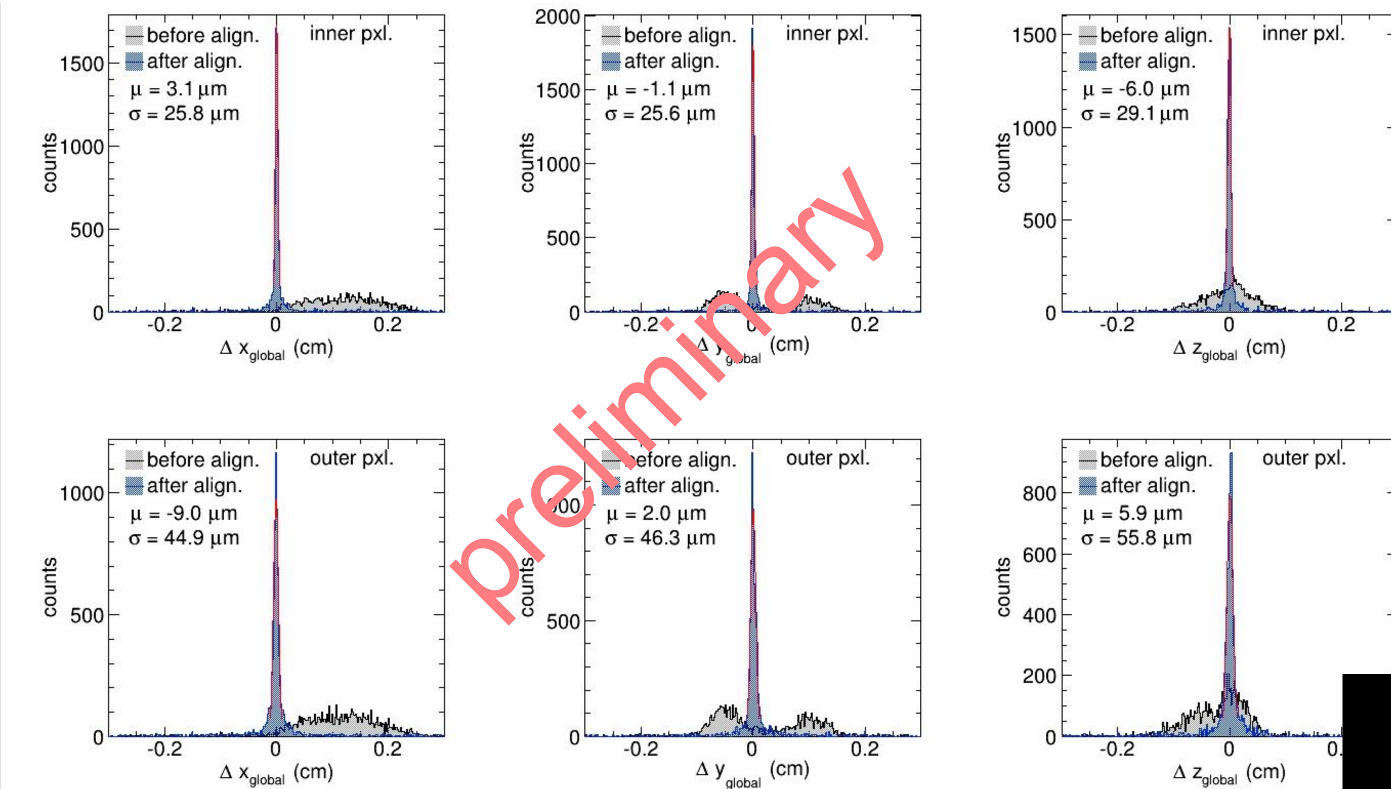
At installation:

- PXL installed with all 400 sensors working, <2k bad pixels
- 38 ladders with Cu flex + 2 inner ladders with Al flex
- Noise rates were tuned for ~1-2 x 10^{-6} per sensor for most sensors



Preliminary Alignment with Cosmics

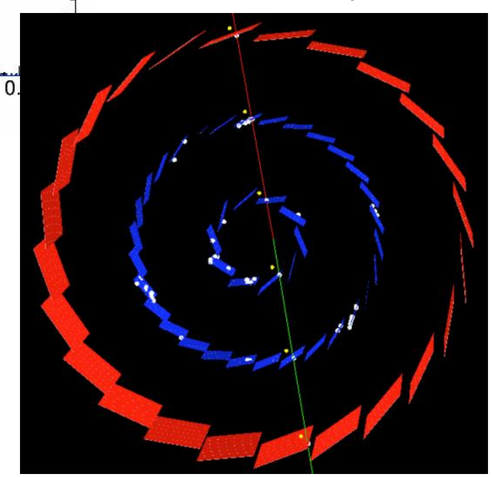
PXL hit residual distributions before and after PXL half to half alignment (analysis by A. Schmah, LBL)



Inner layer

Outer layer

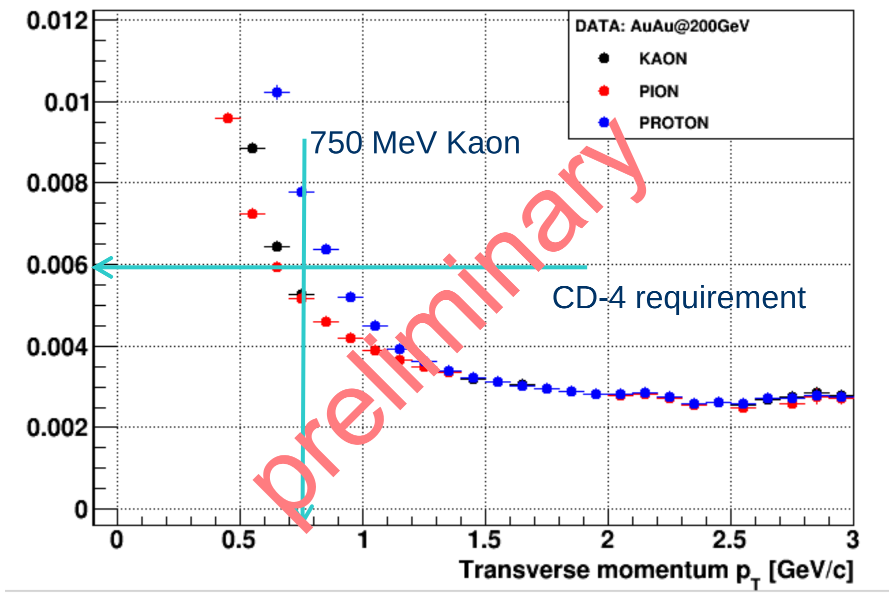
Cosmic ray event



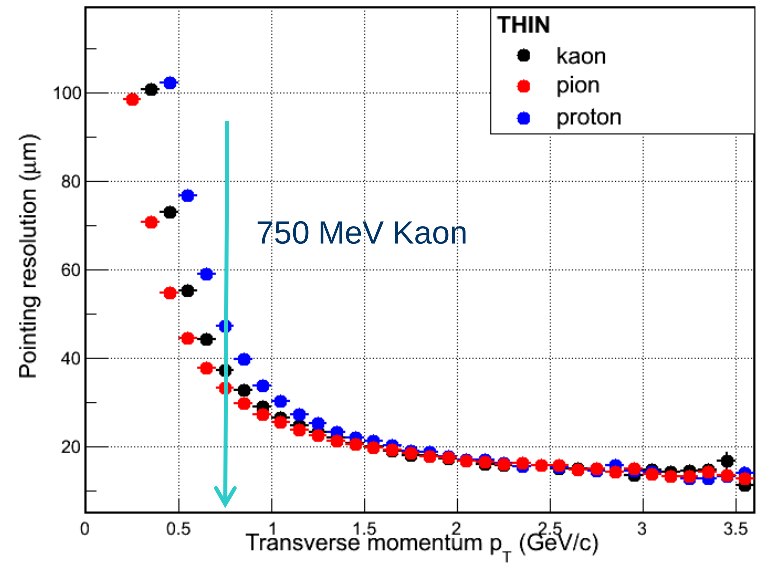
- Consistent with expectations for alignment and momentum of muons

Preliminary DCA Pointing resolution (TPC+IST+PXL)

Preliminary result from the STAR HFT software group

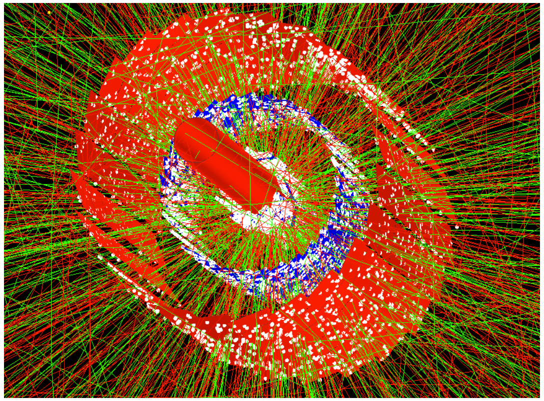


200 GeV/c Au-Au data

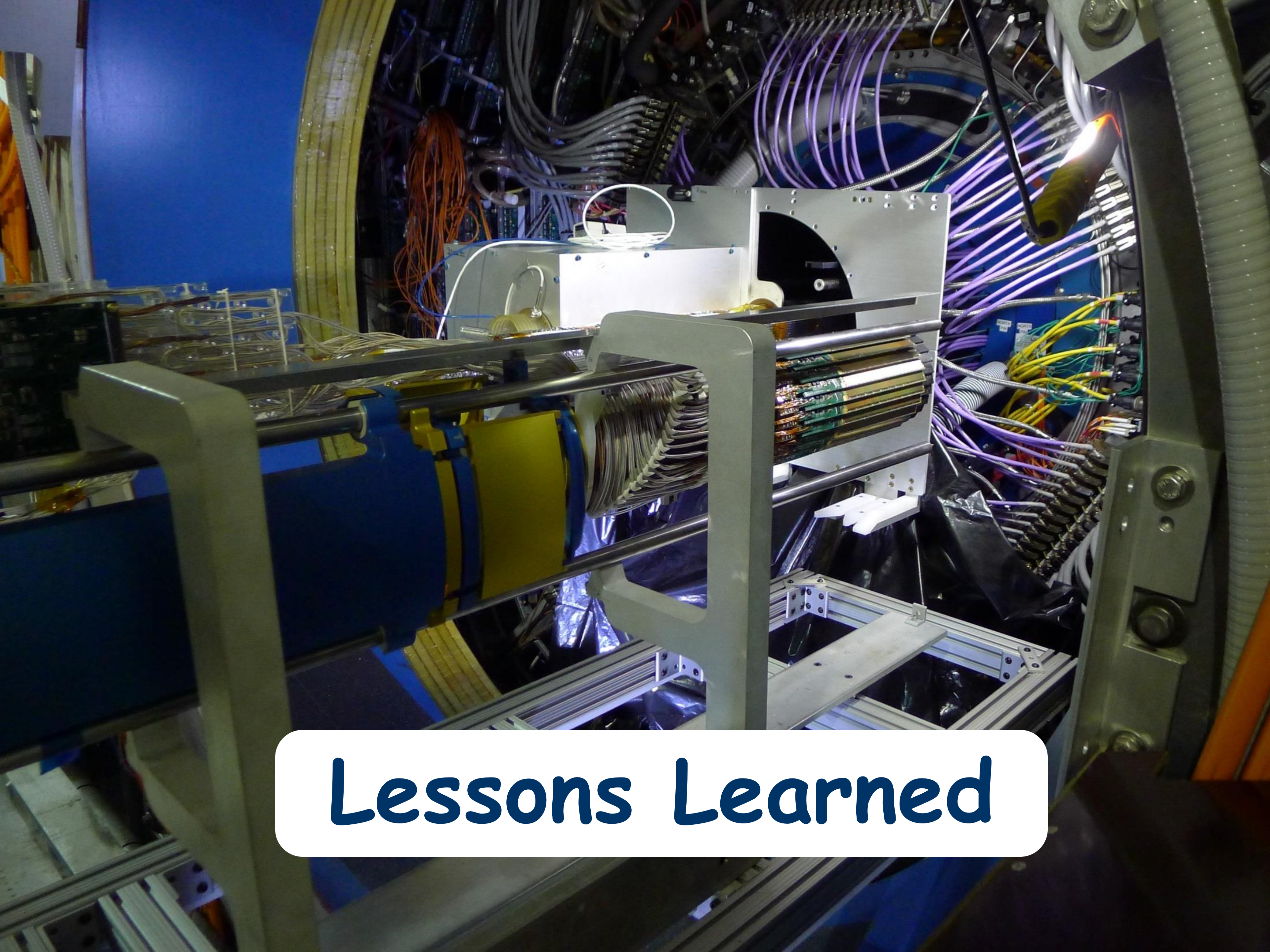


Simulation with Al Cable

200 GeV Au+Au event



- Alignment – work in progress
- DCA pointing resolution matches the CD-4 requirement:
  60 µm for kaons with p_T = 750 MeV/c



Lessons Learned

PXL Probe Testing

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

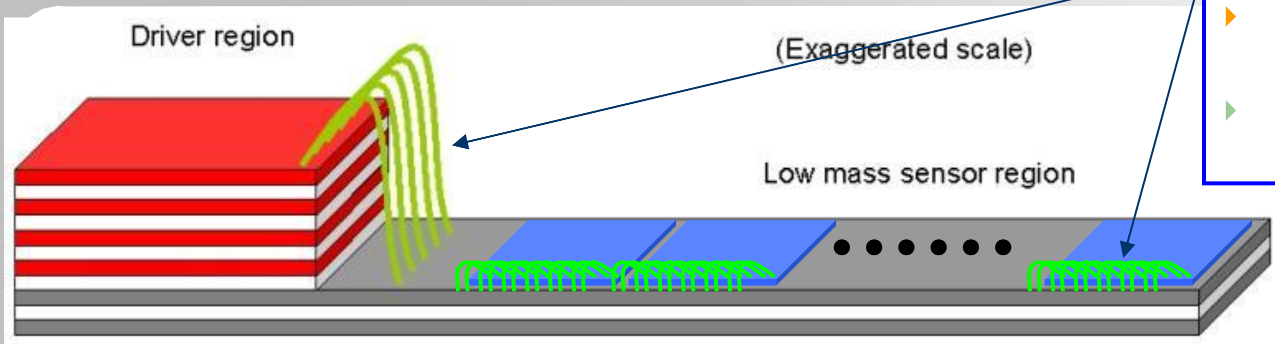
- Custom made vacuum chuck
- Testing up to 18 sensors per batch (optimized for sensor handling in 9-sensor carrier boxes)
- Manual alignment (~1 hr)
- LabWindows GUI for system control
- Automated interface to a database

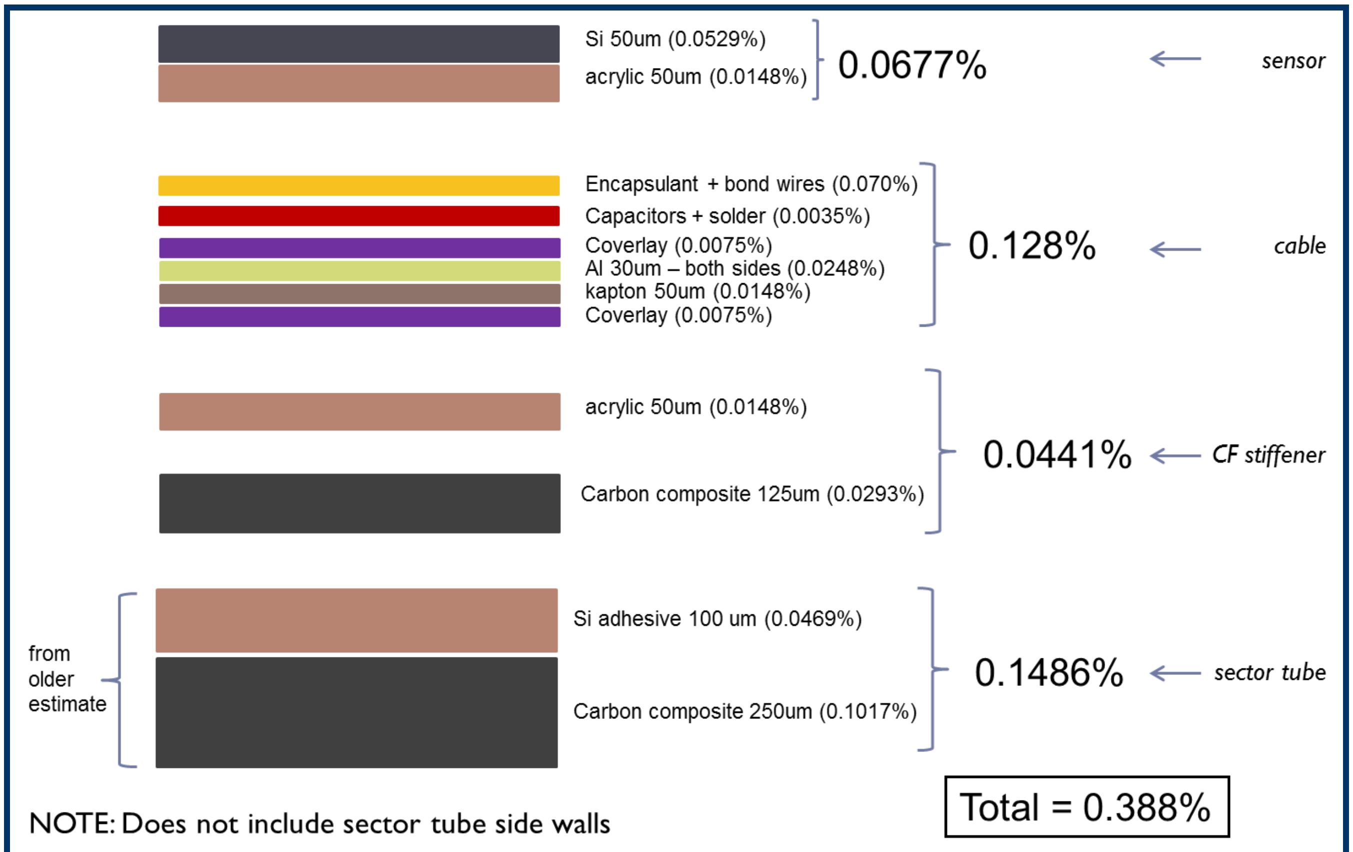
- Probe card with readout electronics
- Sensor tests (~15 min):
  - Parameter characterization at different bias V (@ 2.9V, 3V, 3.3 V)
  - I/V measurements (analog, digital, clamping V)
  - Bias optimization
  - Temporal noise and FPN measurements
  - Fast readout mode
  - Accidental hit rate scan
  - Response to LED pulse (@ 3.3V)

- Sensors built-in testing functionality
- Proper probe pin design for curved thinned sensors
- Yield varied 46% - 60%
- Administrative control of sensor ID

PXL ladder

- Classic wire bonding
- Difficulties and delays with Al cable production
- Backup solution with Cu cables





Flex cable
(*Copper version*)

PXL Ladder Assembly

Sensor positioning

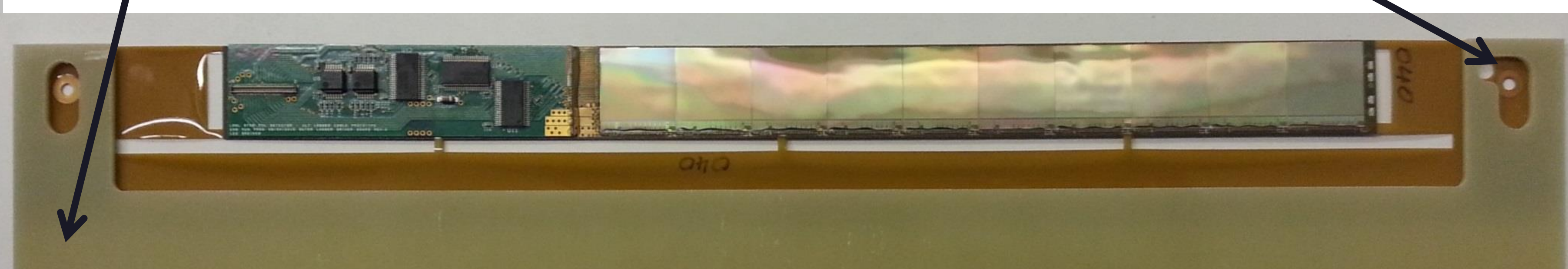
- Precision vacuum chuck fixtures to position sensors
  - by hand
  - with butted edges
- Acrylic adhesive prevents CTE difference based damage
- DRIE dicing improves alignment

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



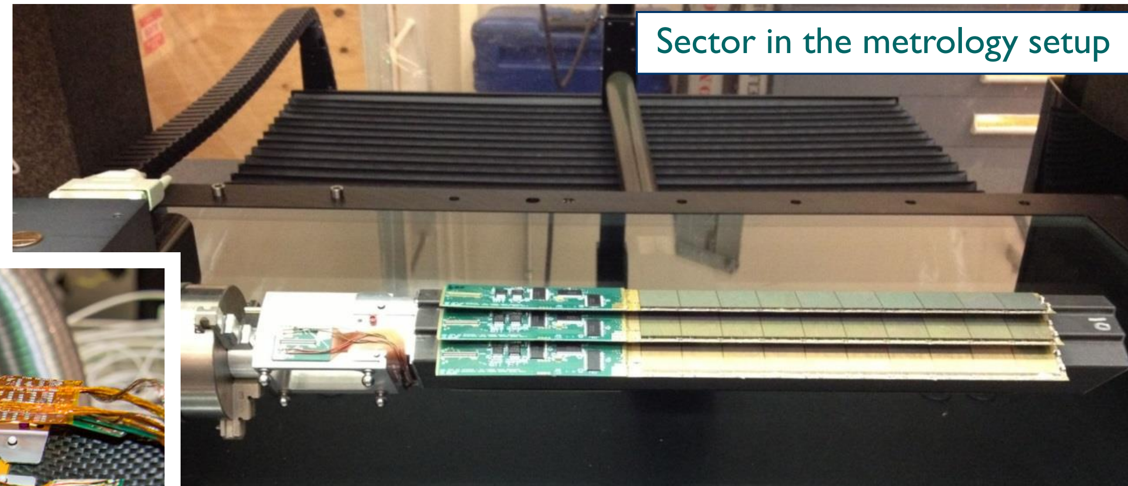
STAR HFT

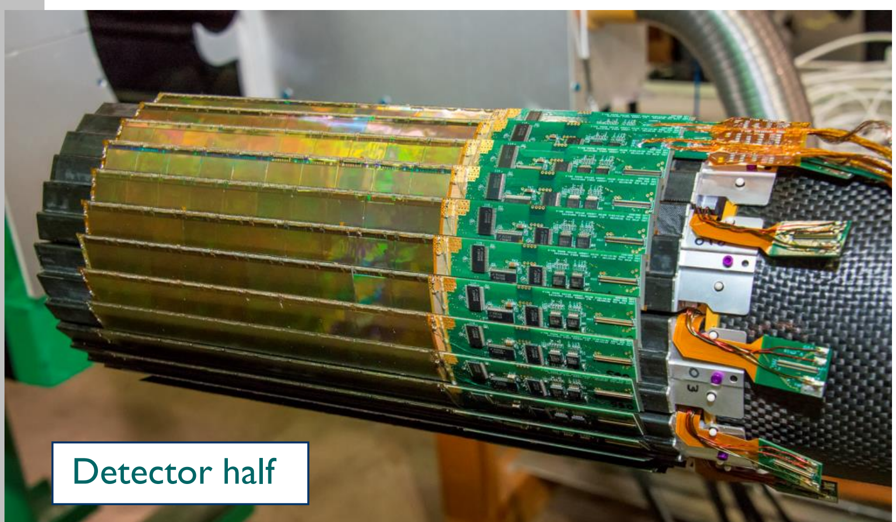
Sector and detector half assembly


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


Sector in the metrology setup


Detector half

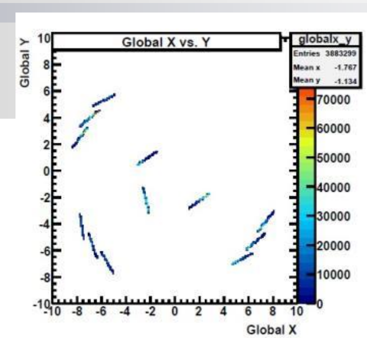
Detector half

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

- Initially lower yield (debugging)

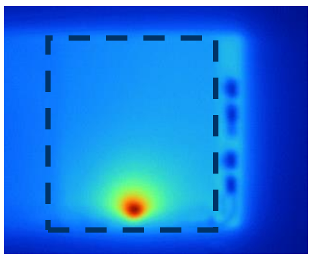
	ladder yield			
	after assembly + bonding	*after encapsulation*	*after sector mounting*	*after metrology*
Tested	92	59	53	48
yield	**0.91**	**0.92**	**0.91**	**1.00**

Engineering run 2013

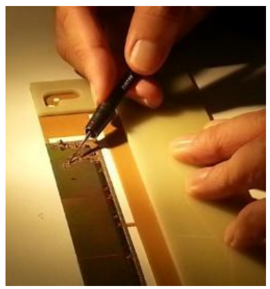


Engineering run geometry

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



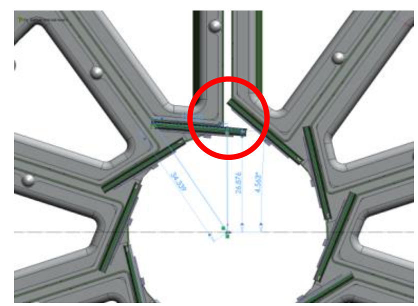
Sensor IR picture



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

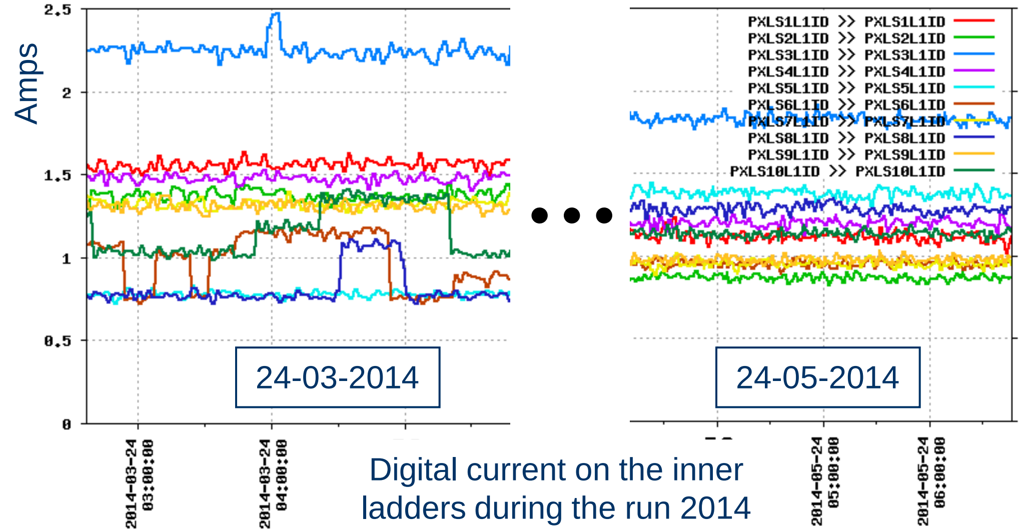


Inner layer design

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

PXL radiation damage in run 2014

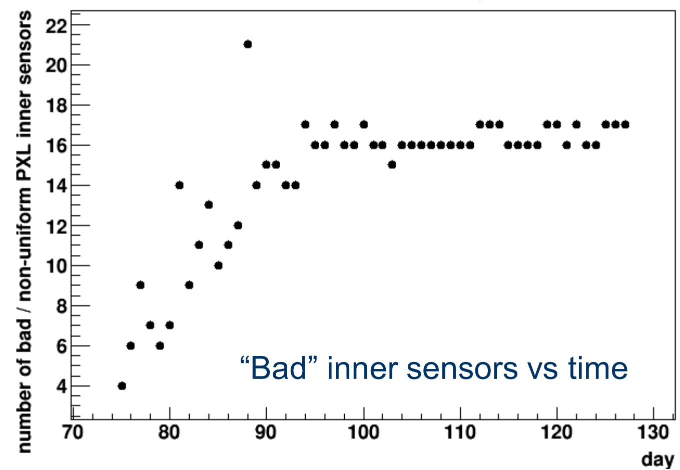
- First damage observed in the15 GeV running after several beam loss events
- continued into 200 GeV run
- Appears to be radiation related (possibly latch-up events):
  - increased digital current, damaged JTAG registers, loss of sub-arrays, etc.
  - mostly in inner ladders (14% of inner layer, 1% of outer layer)



Digital current on the inner ladders during the run 2014

Remediation:

- Latchup thresholds lowered to 120 mA (initially 400 mA) above measured operational current for each ladder
- Cycle digital power and reload configuration automatically every 15 minutes
- HFT is only turned on when collision rate < 55 kHz



“Bad” inner sensors vs time

- SEE tests were performed with earlier prototypes, not the production ones
- Operational methods seem to halt radiation induced damage
- Second detector will be protected from day one

Summary and outlook

- STAR Heavy Flavor Tracker has been installed and commissioned for the 2014 Au+Au RHIC run
- The DCA pointing resolution performance of the installed HFT detectors appears to be as expected
- PXL is the first vertex detector based on the MAPS technology
- Observed radiation related damage in the PXL detector appears to be halted by using operational methods
- We expect to deploy the spare PXL detector (with Al conductor cable on the inner ladders) for the next run and replace damaged ladders in the existing detector with the spare ladders being fabricated
- **MAPS appear to be working well as a technology for vertex detectors**