STAR HFT

The MAPS Based Pixel Vertex Detector for the STAR Experiment

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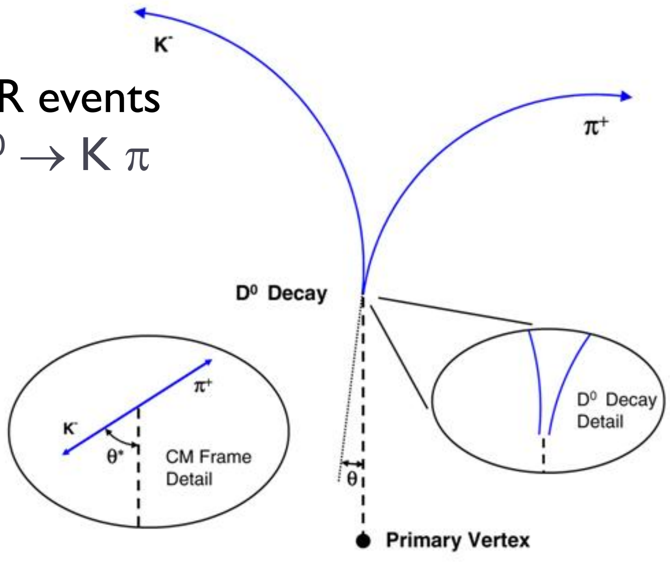
Outline

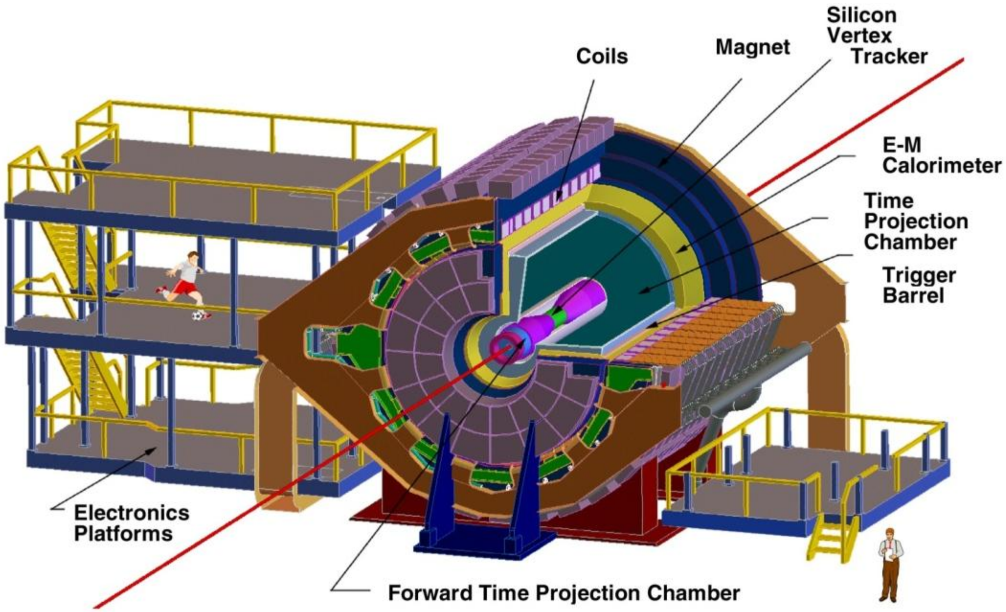
- STAR Heavy Flavor Tracker Upgrade
  - Physics Motivation
  - HFT Detector Description
  - PXL Detector Requirements
- PXL Design Implementation
- PXL Detector production
  - Production Process
  - Engineering Run Detector
  - Final Detector

STAR HFT Upgrade Motivation

Direct topological reconstruction of Charm in STAR events

- Detect charm decays with small cτ, including $D^0 \rightarrow K\ \pi$





Method: Resolve displaced vertices (123 μm)

200 GeV Au-Au collisions @ RHIC

PXL in STAR Inner Detector Upgrades

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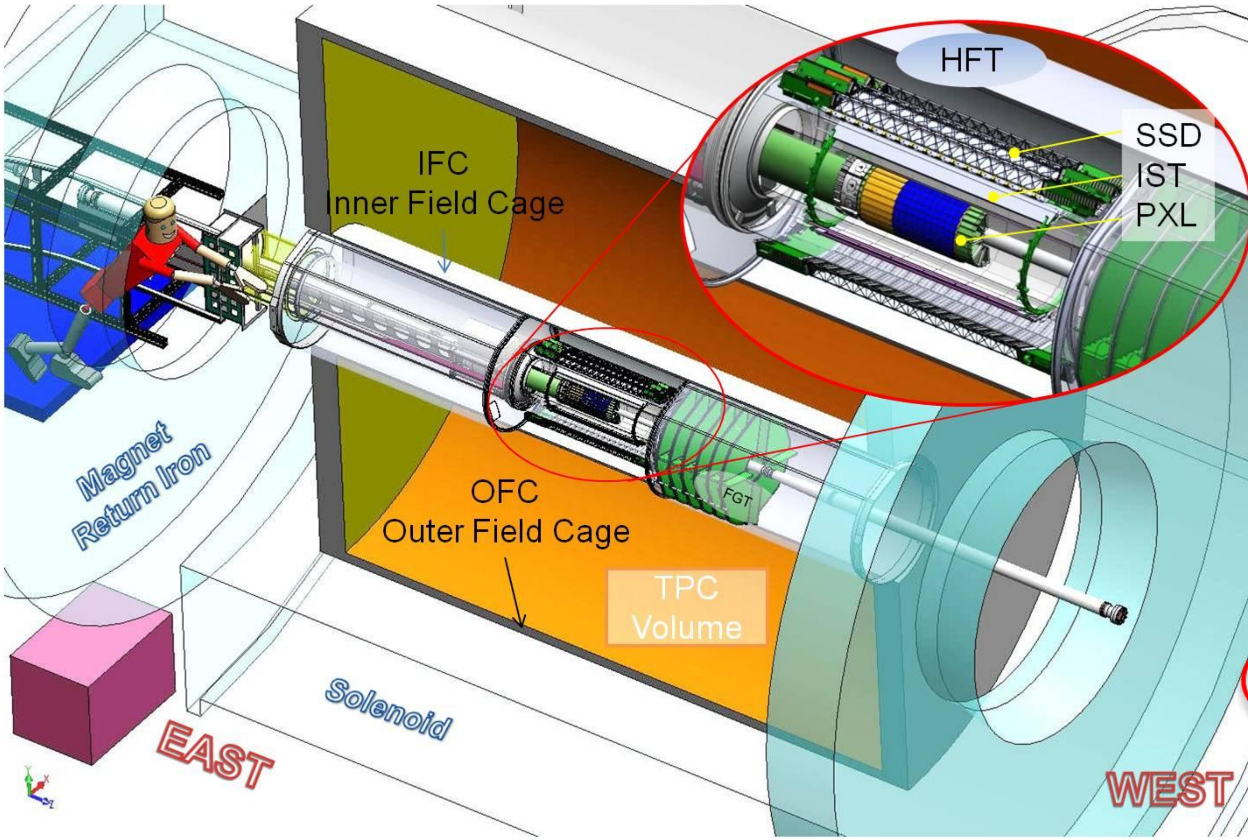

TPC – Time Projection Chamber (main tracking detector in STAR)

HFT – Heavy Flavor Tracker

- SSD – Silicon Strip Detector
  - r = 22 cm
- IST – Intermidiate Silicon Tracke
  - r = 14 cm
- PXL – Pixel Detector
  - r = 8 cm
  - r = 2.7 cm

We track inward from the TPC with graded resolution:

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

PXL Detector Requirements and Design Choices

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Requirements

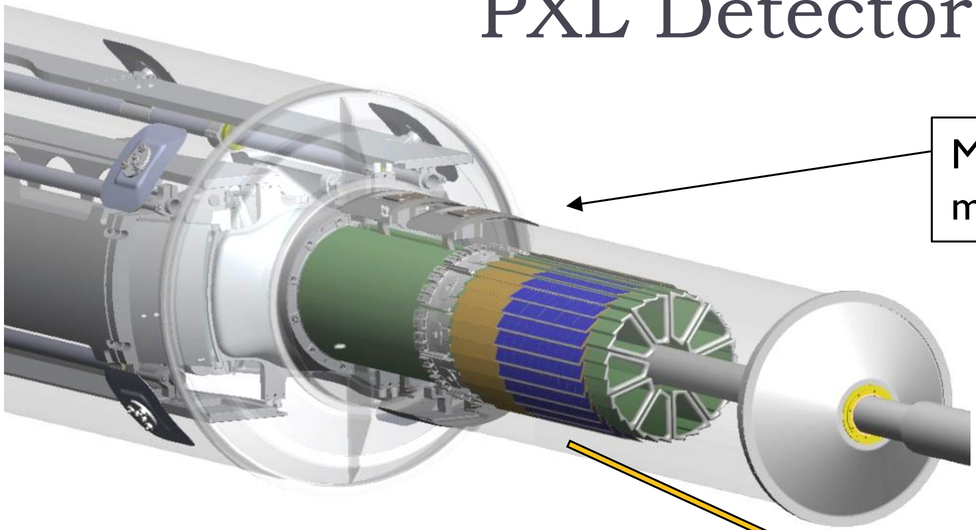
- -1 ≤ Eta ≤ 1, full Phi coverage (TPC coverage)
- ≤ 30 μm DCA pointing resolution required for 750 MeV/c kaon
  - Two or more layers with a separation of > 5 cm
  - Pixel size of ≤ 30 μm
  - Radiation length as low as possible but should be ≤ 0.5% / layer (including support structure). The goal is 0.37% / layer
- Integration time of < 200 μs
- Sensor efficiency ≥ 99% with accidental rate ≤ 10^{-4}
- Survive radiation environment

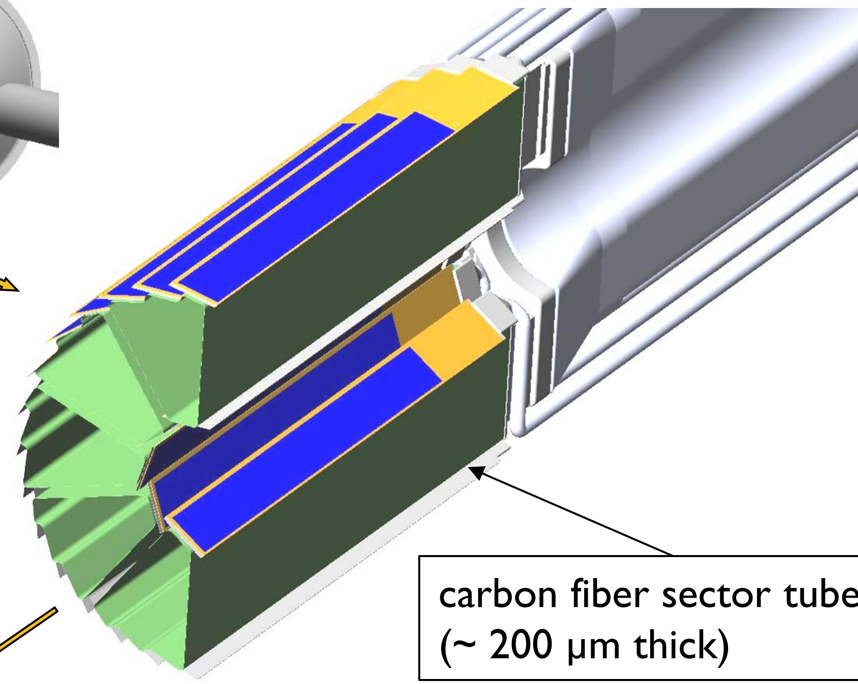
Design Choices

- Air cooling
- MAPS (Monolithic Active Pixel Sensor) pixel technology
  - Sensor power dissipation ~170 mW/cm^2
  - Sensor integration time <200 μs (L=8×10^{27})
- Thinned silicon sensors (50 μm thickness)
- Quick extraction and detector replacement (1 day)

- PXL Design Implementation

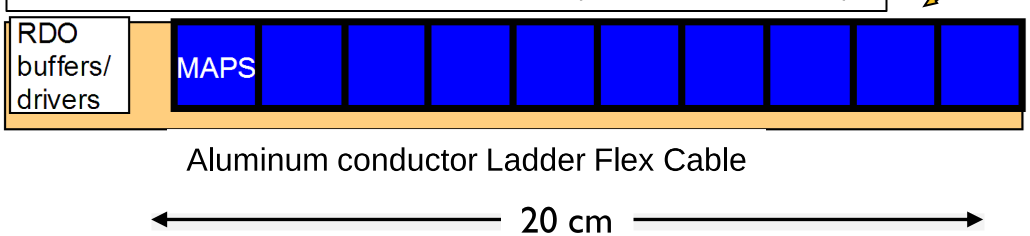
PXL Detector Design



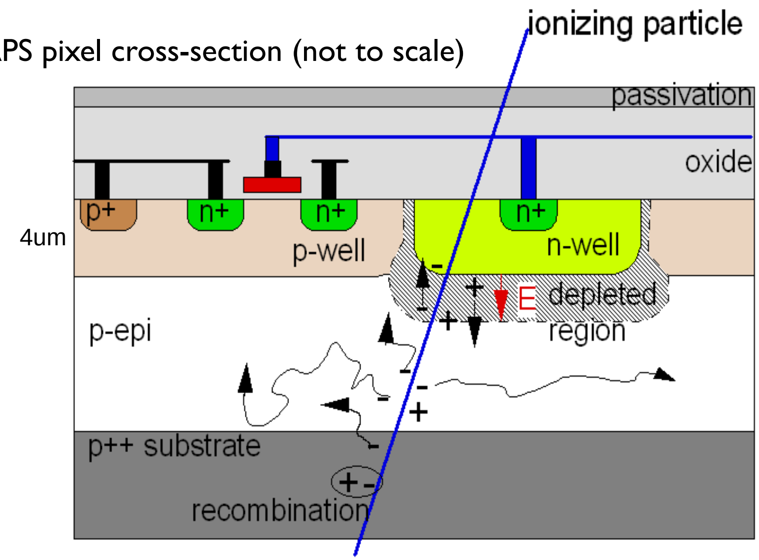


- 4 ladders / sector
- 5 sectors / half (10 sectors total)
- 2 layers
- Insertion from one side

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

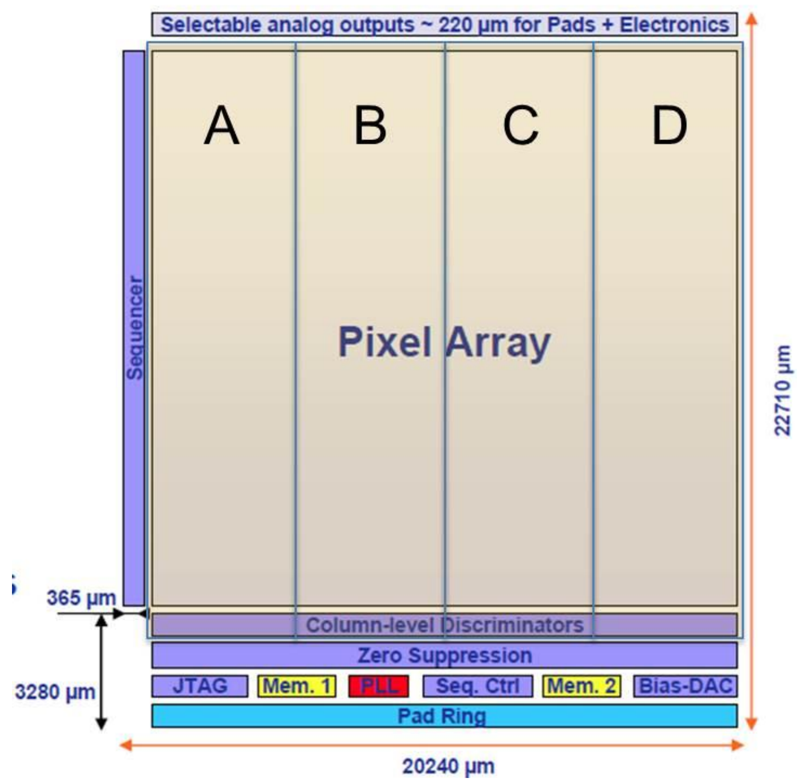


The *Ultimate2* Sensor



- Reticle size (~ 4 cm²)
  - Pixel pitch 20.7 µm
  - 928 x 960 array ~890 k pixels
- Power dissipation ~170 mW/cm² @ 3.3V
- Short integration time 185.6 µs
- 2 LVDS data outputs @ 160 MHz
- 4 sub-arrays to help with process variation
- Built-in automated testing routines for sensor testing and characterization

- Standard commercial CMOS technology
- IPHC – MIMOSA Series
- Room temperature operation
- Proven thinning to 50 µm



The Hybrid Cable

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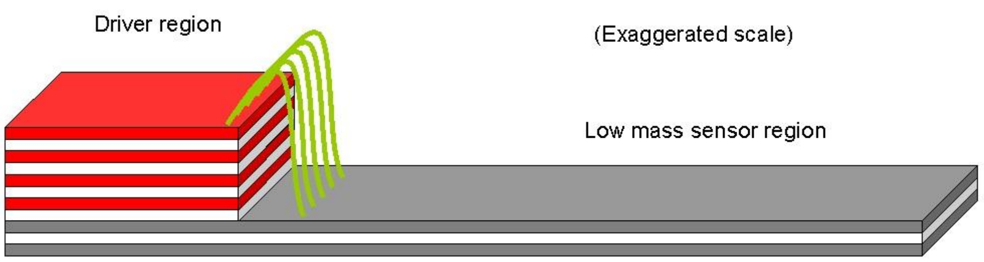
- Sensor readout and powering
- Minimal radiation length
  - Production aluminum conductor flex cables are being fabricated in the CERN PCB shop
  - Copper conductor flex cables for the Engineering Run detector

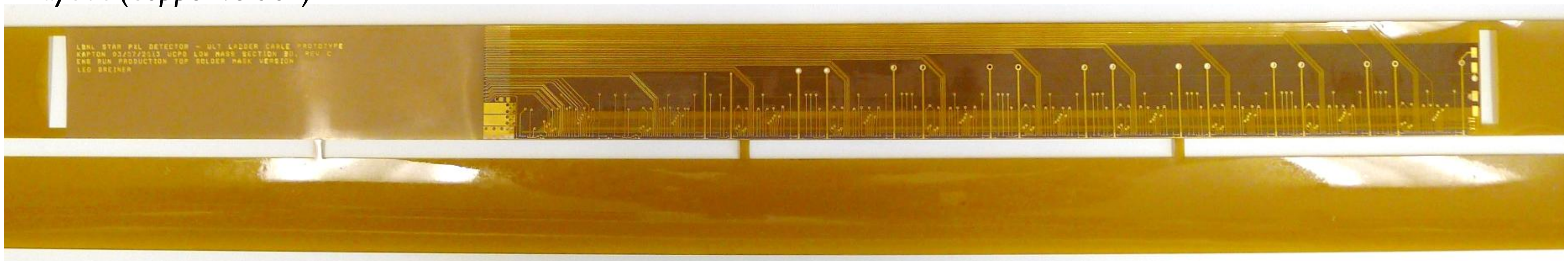
Low mass region calculated X/X_0 for Al conductor = 0.079 %
Low mass region calculated X/X_0 for Cu conductor = 0.232 %



Hybrid Copper / Aluminum conductor flex cable design concept

- 20 differential signal output pairs
- JTAG, 2 temp diodes, CLK, START
- VDD, VDA, GND - ~1.8 A / ladder

Layout (*Copper version*)



PXL Detector Powering and Readout Chain

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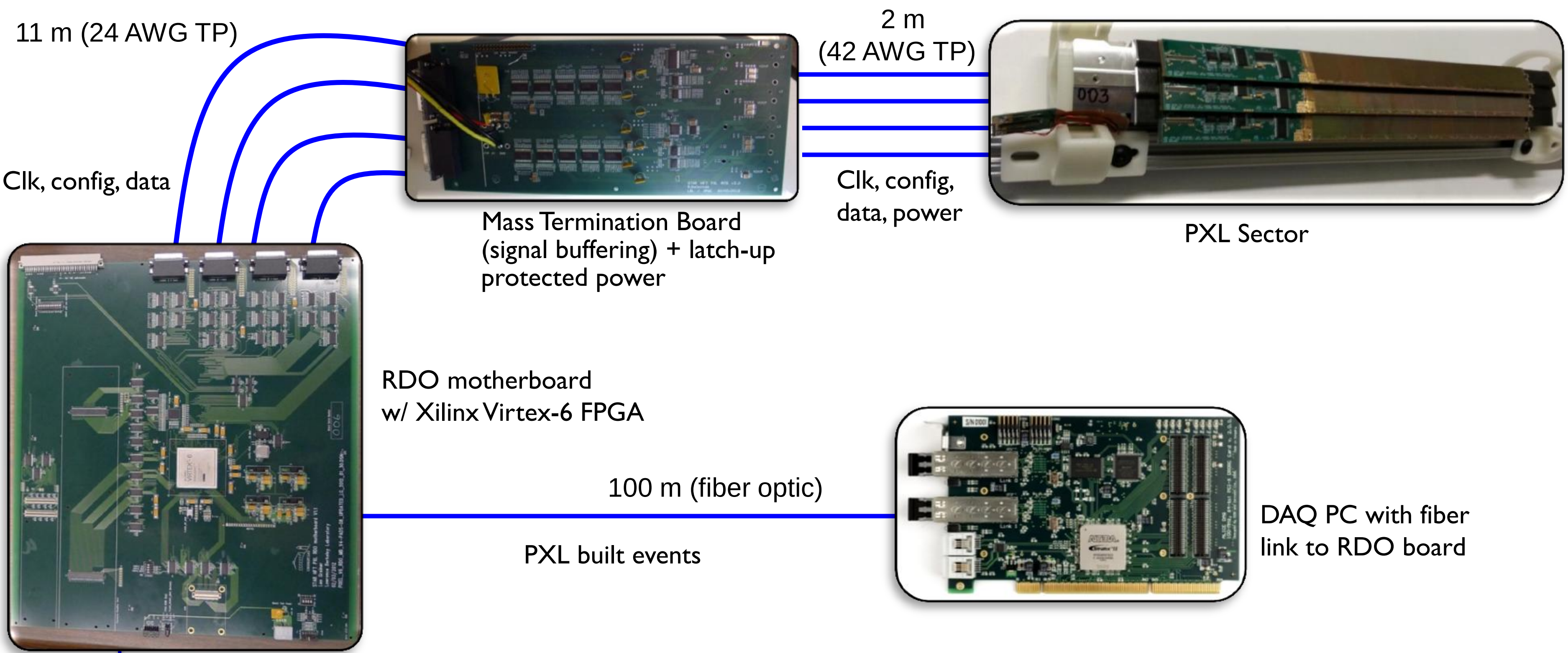


Trigger,
Slow control,
Configuration,
etc.

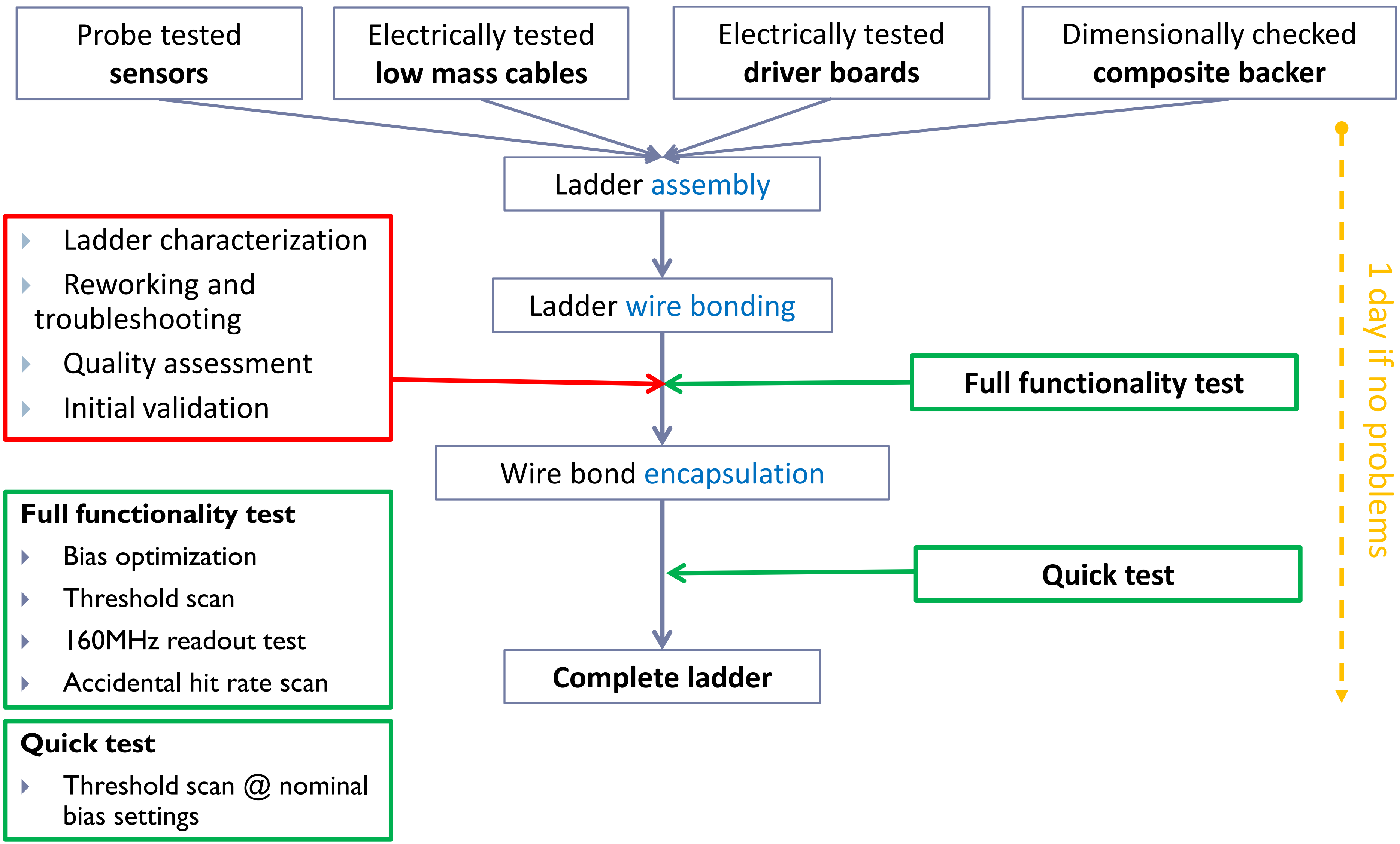
Existing STAR infrastructure

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 Detector Production

PXL Detector Production – *work flow chart 1*



PXL Detector Production – *work flow chart 2*

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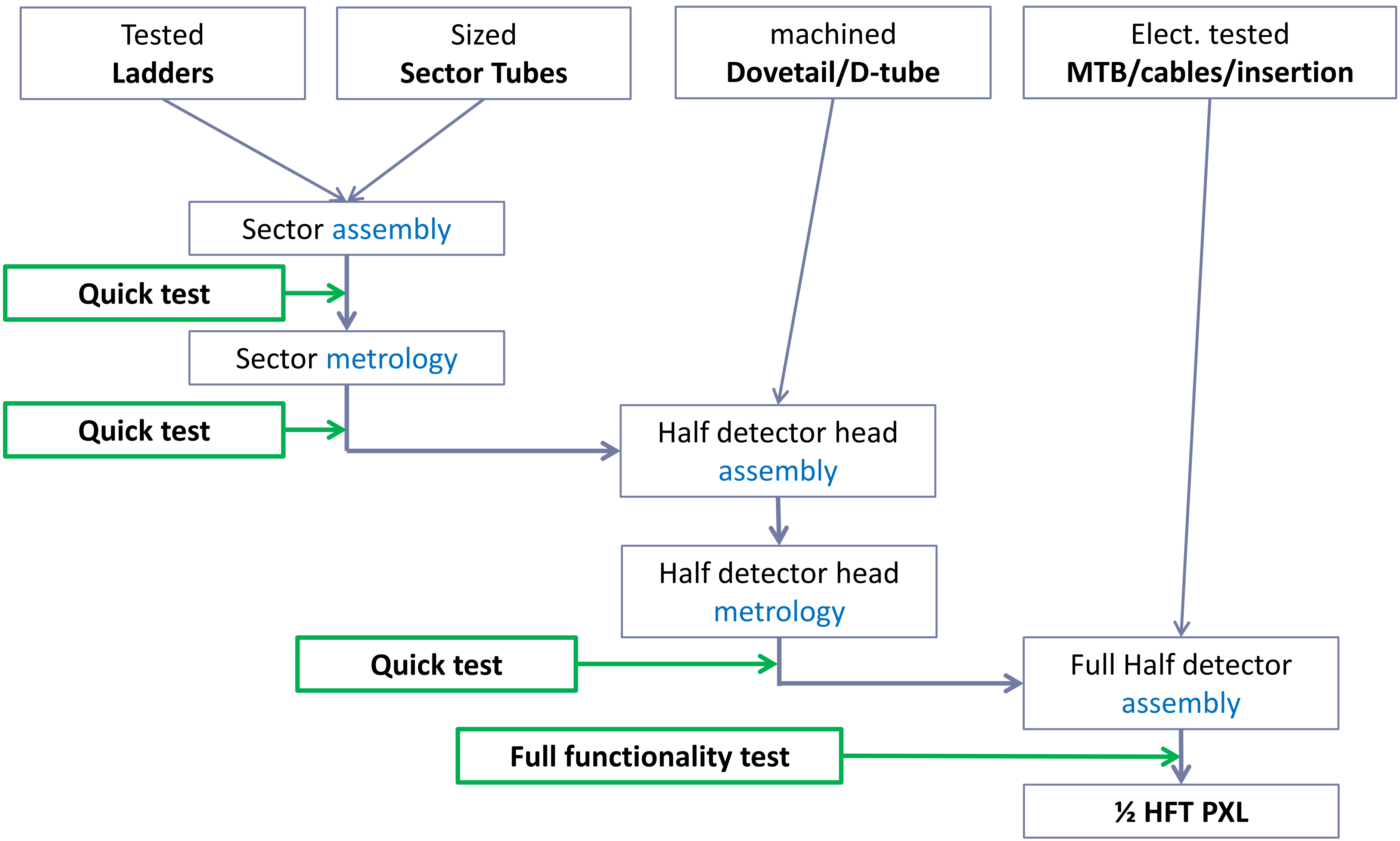
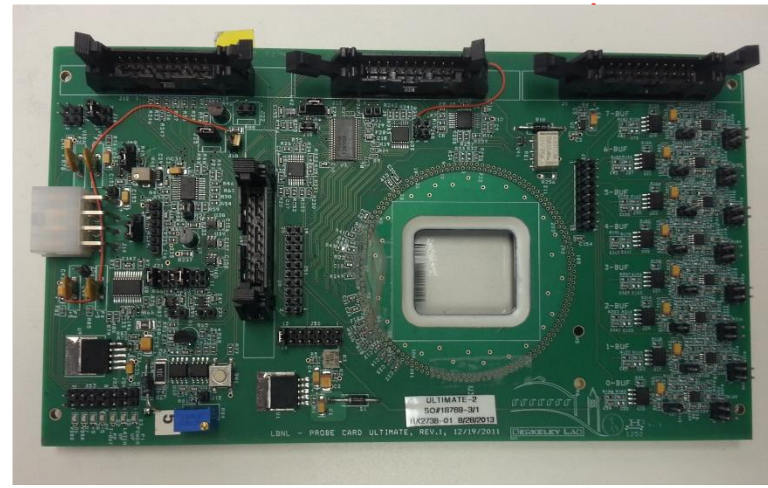


PXL Probe Testing: Setup

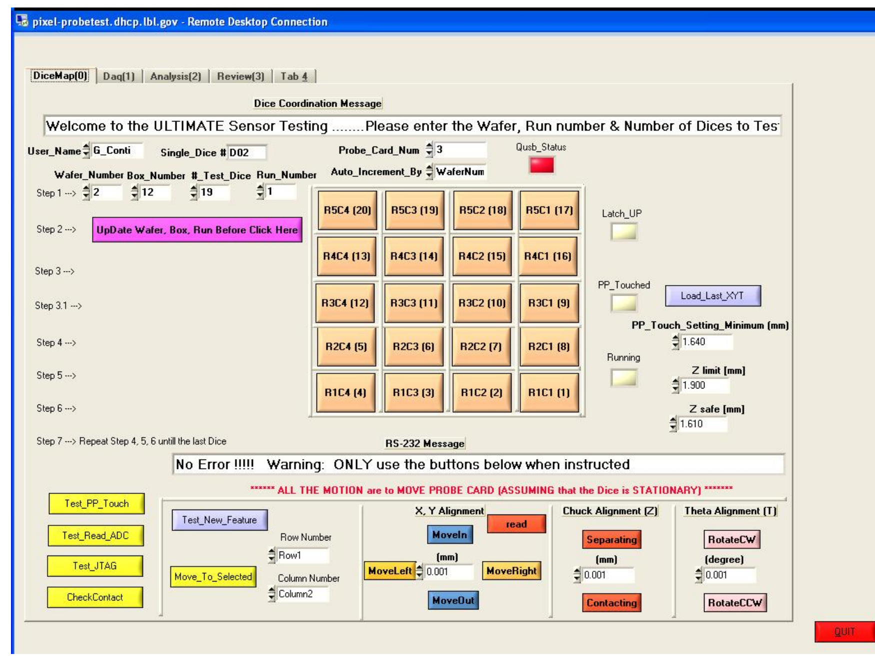
- Full sensor characterization
- Thinned and diced 50 µm thick sensors (curved)
- Full speed readout (160 MHz)



Probe card with readout electronics
Analog and digital sensor readout

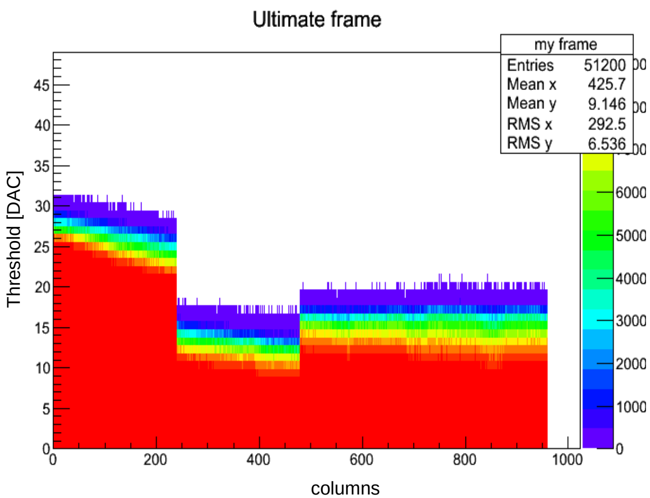
Vacuum chuck for testing 20 thin sensors (50 µm)
Testing up to 18 sensors per batch
Manual alignment

LabWindows GUI



PXL Probe Testing: Parameters

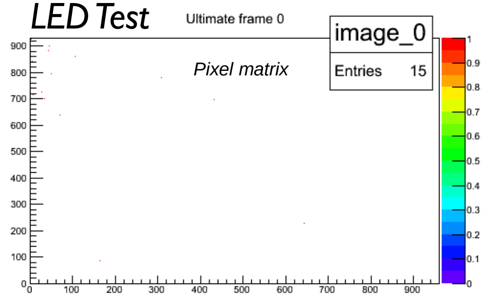
- Parameter characterization at different bias V (@ 2.9V, 3V, 3.3 V)
  - I/V measurements (analog, digital, clamping V)
  - Optimal potential levels
  - Noise
  - Fast readout mode
  - Accidental hit rate scan
  - Response to LED pulse (@ 3.3V)



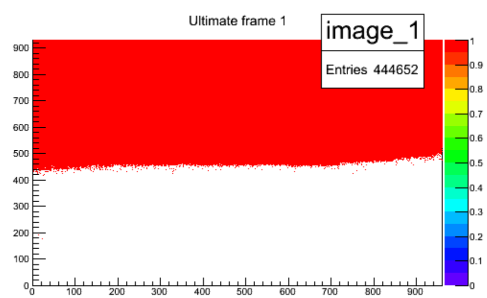
Sensor threshold scan

- Automated interface to a database
  - Optimal parameters used for final detector configuration

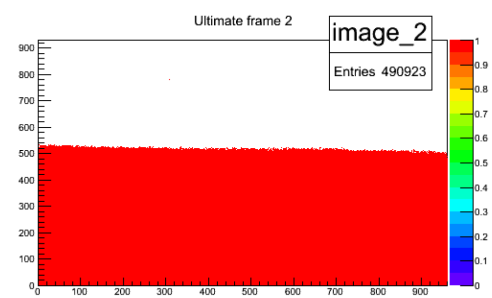
LED Test



1) dark frame

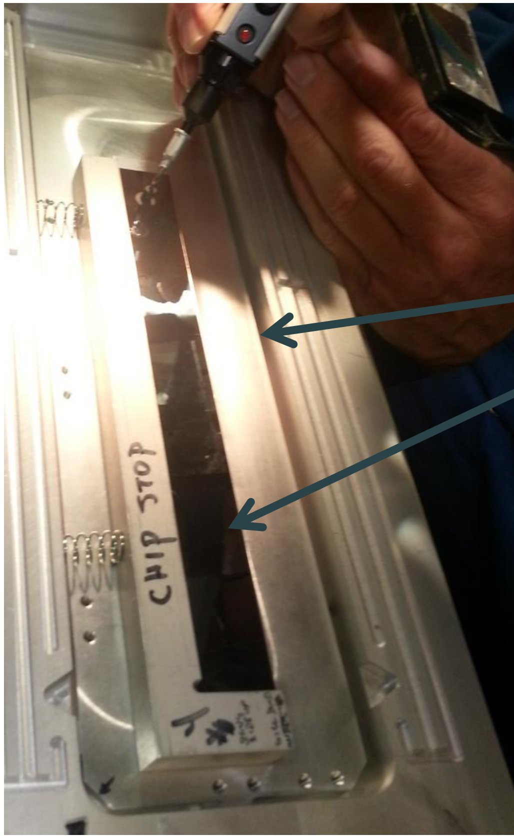


2) 1st part of LED data



3) 2nd part of LED data

Ladder Assembly



Precision vacuum chuck fixtures to position sensors

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

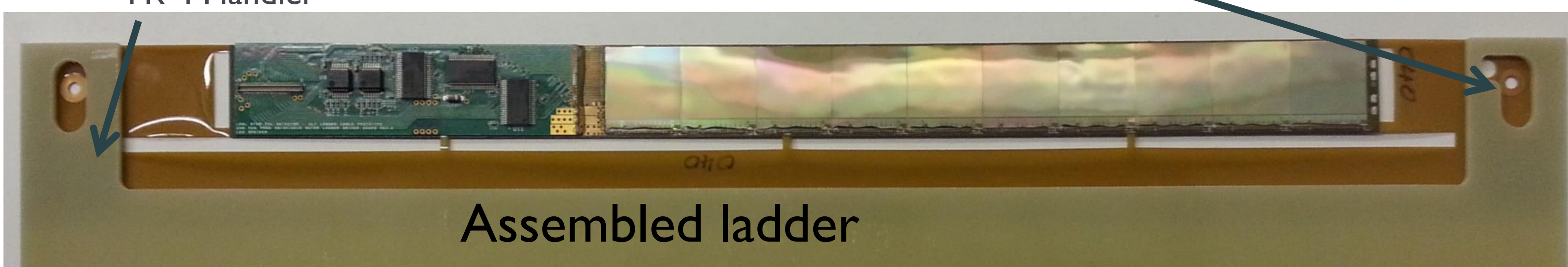
Weights taken at all assembly steps to track material and as QA.

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

Sensor positioning

Cable reference holes for assembly

FR-4 Handler



From ladders to sectors… to detector halves

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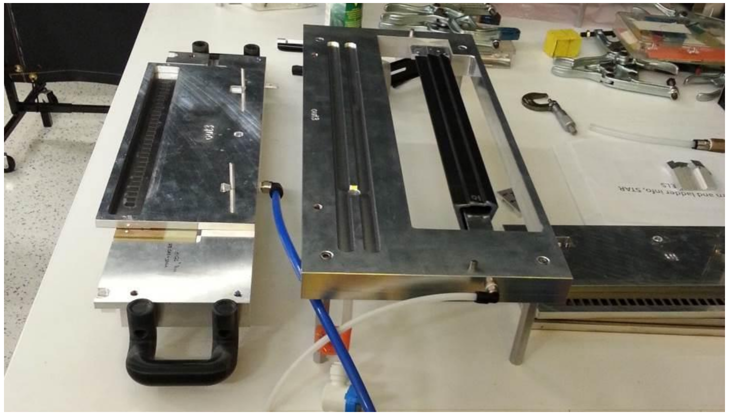
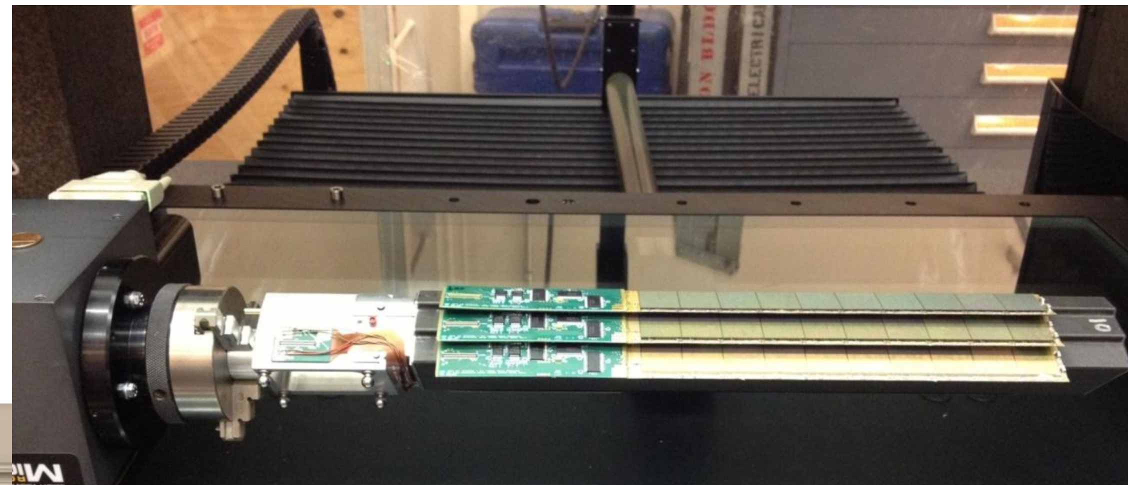


Sector assembly fixture

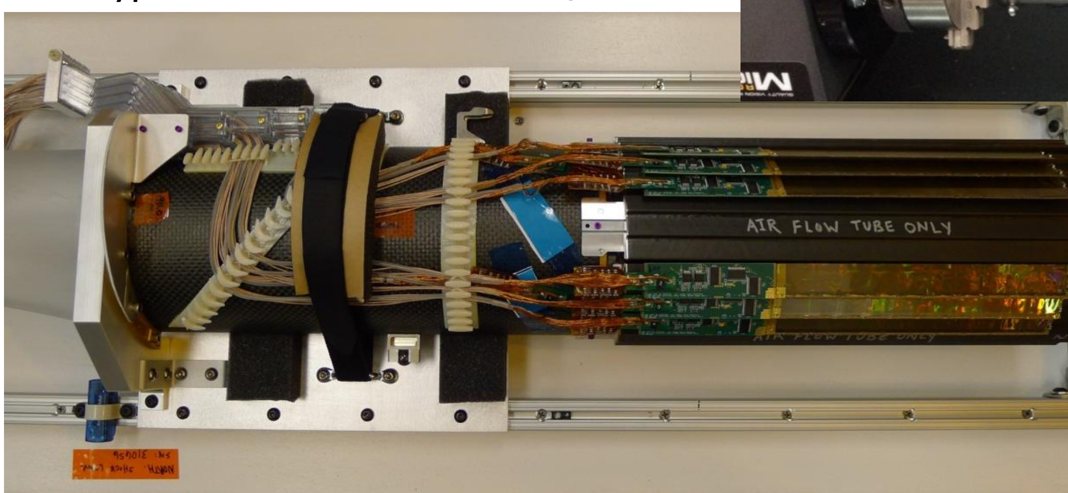
Sectors

- 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

Prototype sectors in a detector half



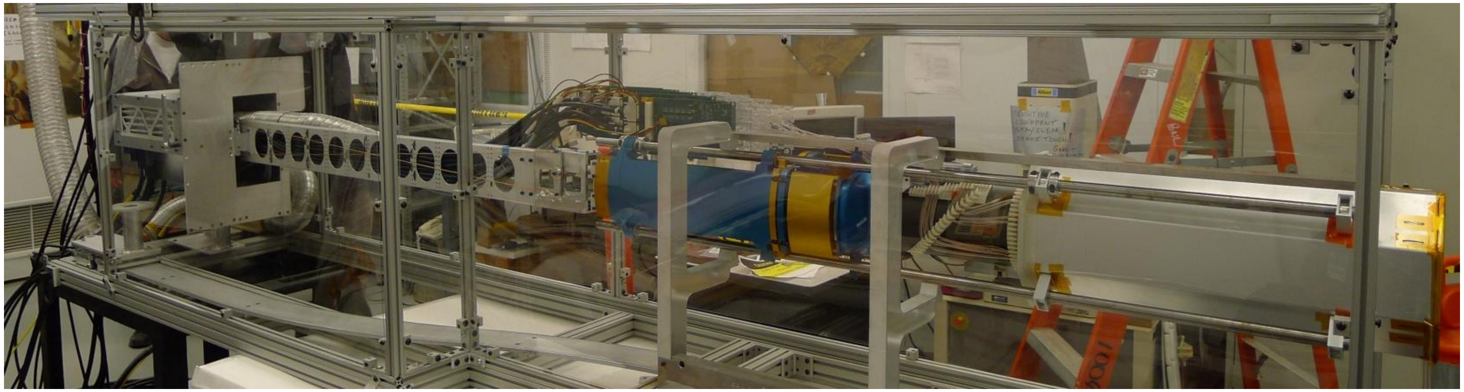
Detector half

- 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

Engineering Run Detector

- **Goals**:
  - Produce and assemble as many working sectors as possible to face the detector-level problems
  - Test full insertion mechanism, parallel powering, trigger, readout
  - Test cooling performance
- **The Prototype Detector**
  - **3 full sectors** distributed over the 2 detector halves
  - **Functional sensors**
    - A certain inefficiency is accepted in the prototype detector
  - Production detector **powering and readout chain** design and **mechanics**

Half PXL detector with insertion mechanics, @STAR clean room



Engineering Run Detector Installation

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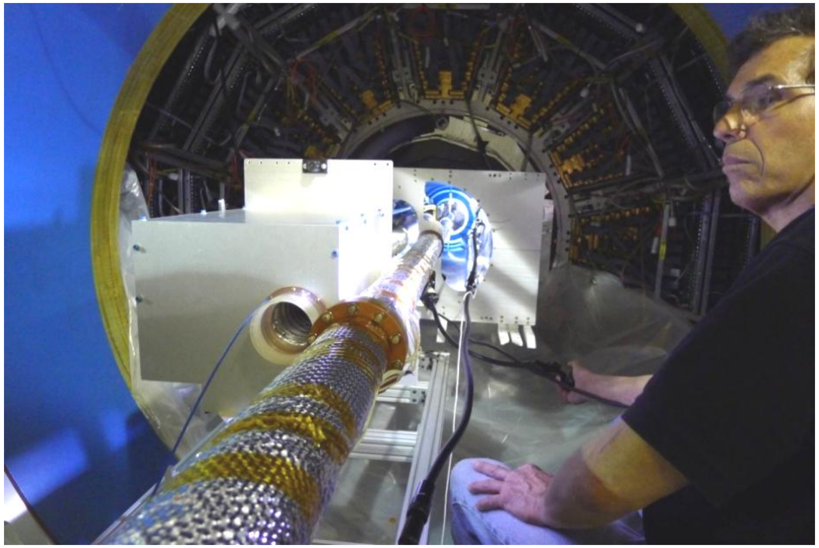
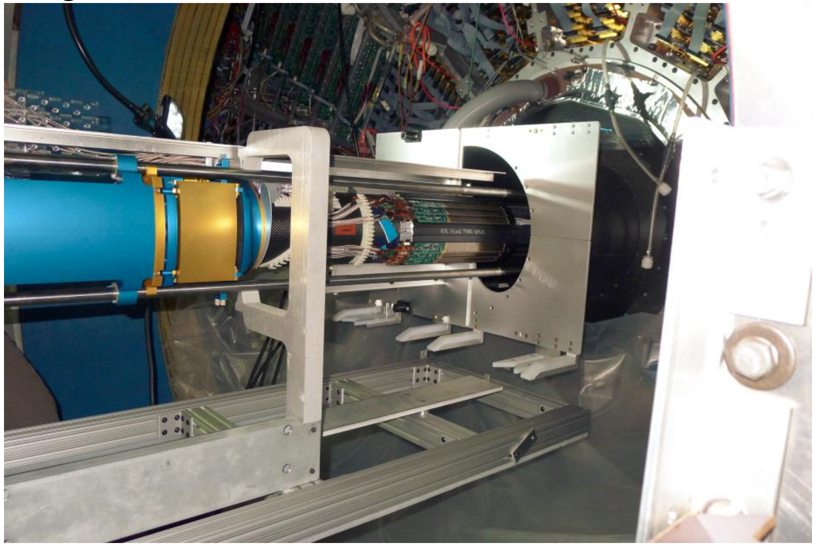
- Detector preparation @ STAR Clean Room
  - Half detectors integrated in the insertion mechanics w/ full RDO and Power chains
  - Detector functionalities tested
- Insertion and full chain connection
  - Effectively completed within an 8-hours shift

Integration with insertion mechanics

Left side insertion



Right side insertion



Engineering Run Detector inserted

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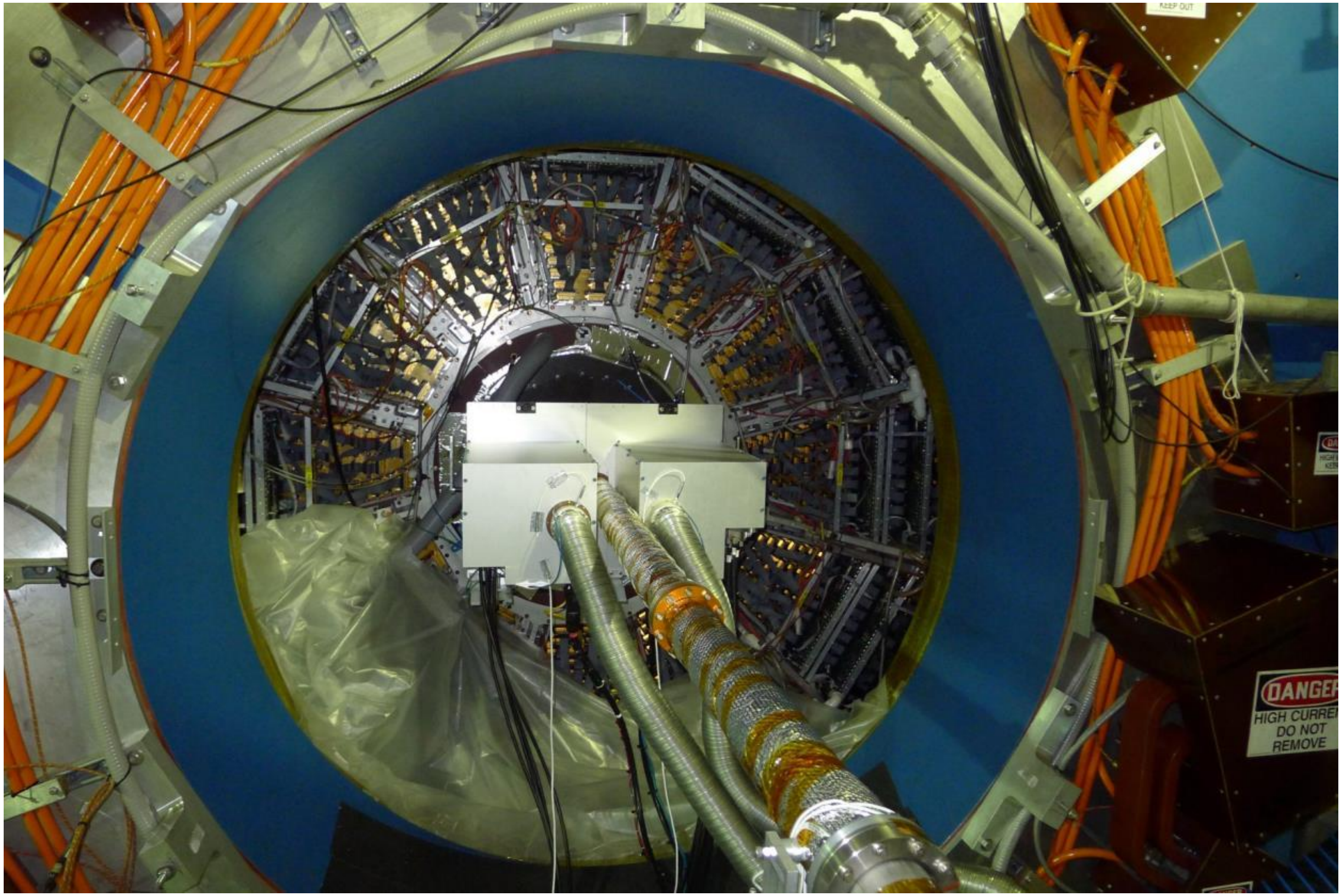

Successfully inserted, cabled, powered → fully working

Engineering Run operations

- Insertion on May, 8 2013 (during 16h stop of beam activities)

- PXL Engineering Run schedule
  1. **Commissioning (**First 10 days, mainly when no beam):
     - Firmware completion and integration
     - Sensor threshold tuning and initialization procedure implementation
     - Integration with the STAR Slow Control, Trigger, DAQ, Cooling infrastructure
  2. **Low Luminosity Runs** (Second part of the Run)
     - 2% of full luminosity thanks to beam displacement to reduce pile up and irradiation
     - Data acquisition with STAR detector to collect data for tracking performance analysis
  3. **High Luminosity Runs** (Last 3 days of the Run)
     - Nominal 400kHz collision rate, pre-scaled trigger rate to minimize PXL data
     - SEU test
     - High irradiation

- Collected Data & Events
  - ~ 600 GB low multiplicity PXL data (~10 million events) + ~ 180 GB of high multiplicity

- Detector now back @ LBL for post-run examination
  - Current draw increase and sensor behavior under study

Preliminary results from Engineering Run

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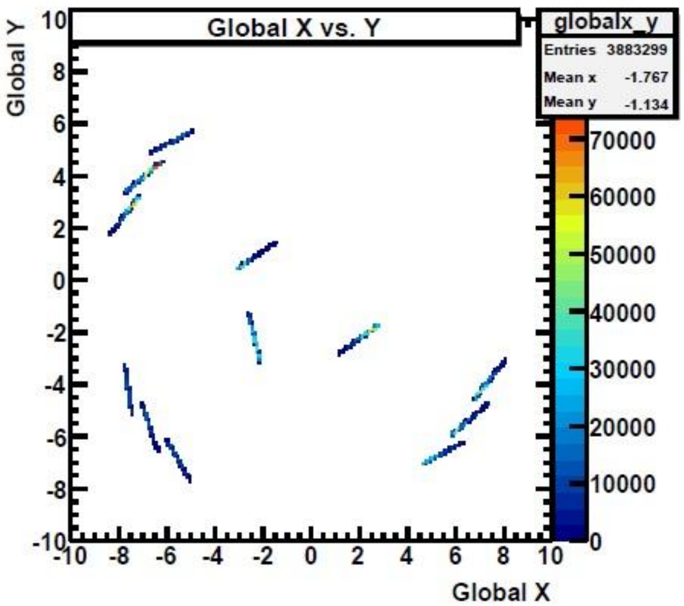
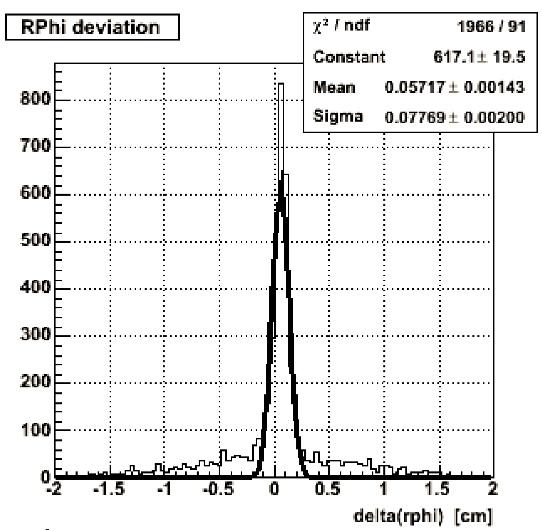
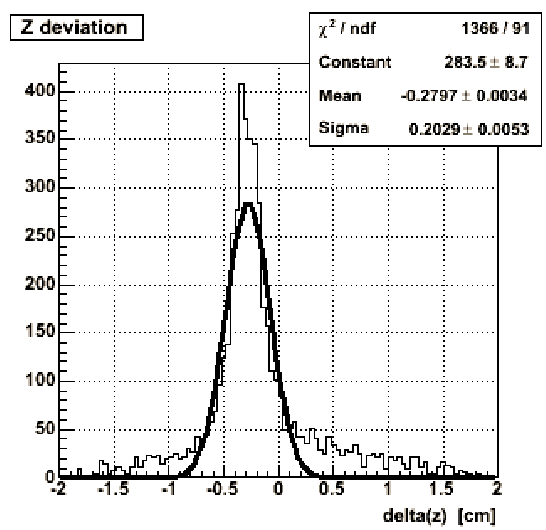


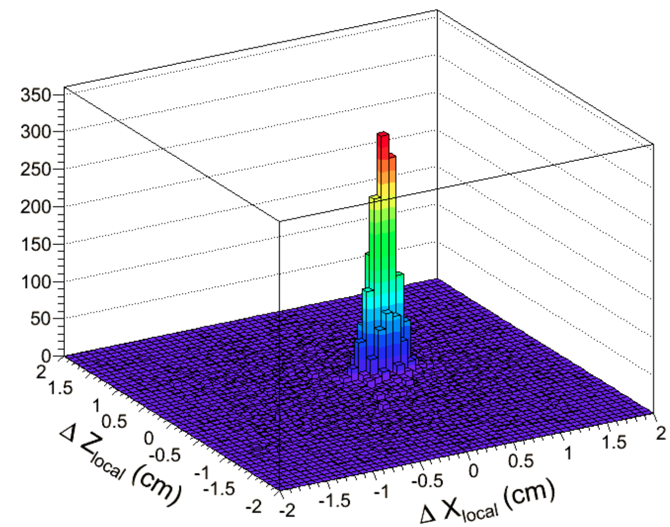
Hit display for PXL Engineering Run detector.

TPCtrack-PXLhit residuals

- First tracking results show good matching of TPC tracks to hits on PXL sensors
- Residuals compatible with TPCtrack resolutions on the sensors (~1-2 mm)
- 3 mm beam shift reflects the PXL&TPC relative position



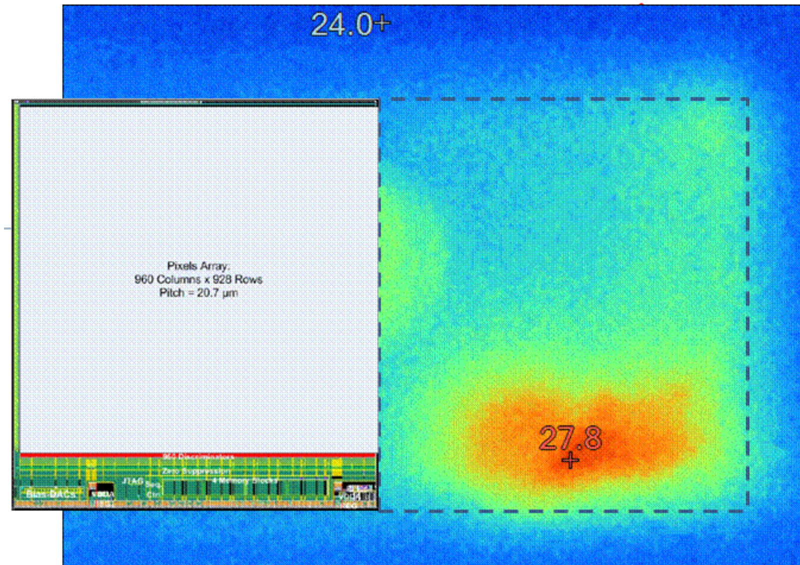




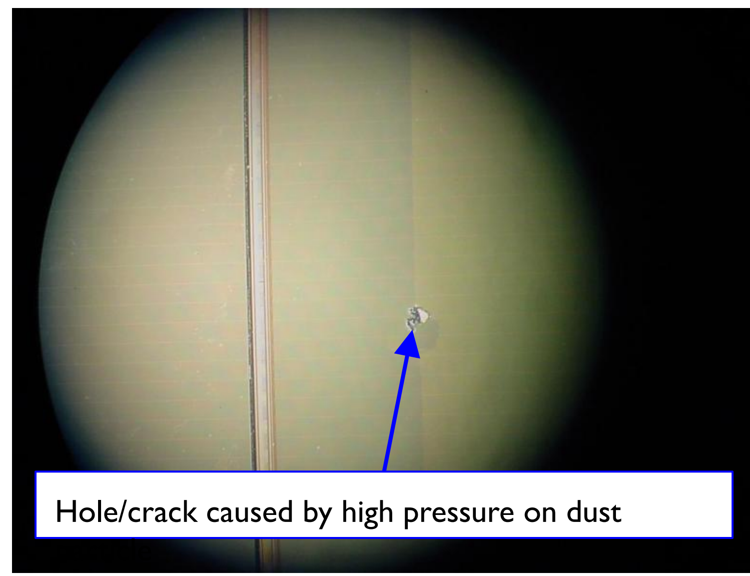
Lessons learned

The fabrication of complete sectors allowed discovering and correcting the production problems

1. Single sensor flaws appeared on ladder
   - Limits on functional parameters, e.g. current draw, added to rejection criteria for sensors
   - Specific fast readout mode tests added
2. Cracks in sensors during vacuum bag cycling and sector assembly
   - Sensor and tool cleaning improved
   - Sector assembly fixtures machined to safely accommodate the silicon
3. Mismatch in bonding wire assignment and pad-to-trace misalignment
   - Bonding diagram optimized for the new sensor layout
   - Sensor dimension stability with DRIE dicing

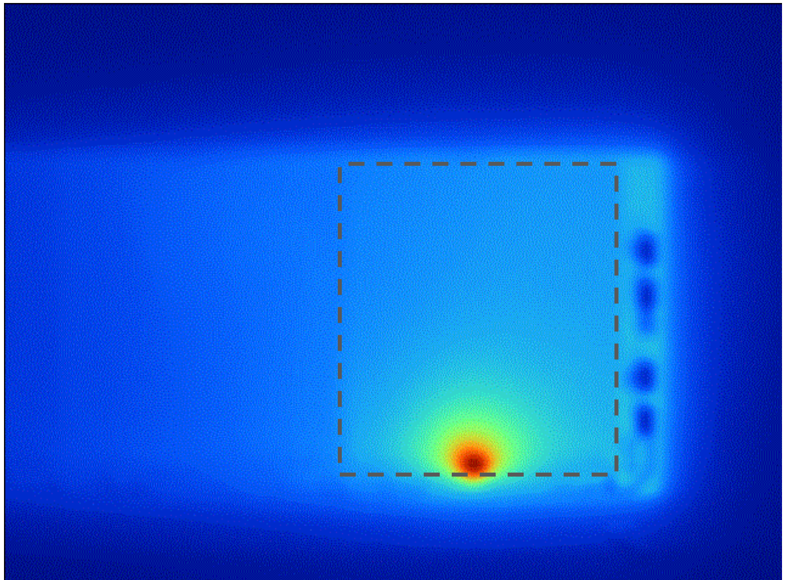


Memory block power circuit internally shorted to ground:
High current draw in probe testing
Hot region from IR inspection



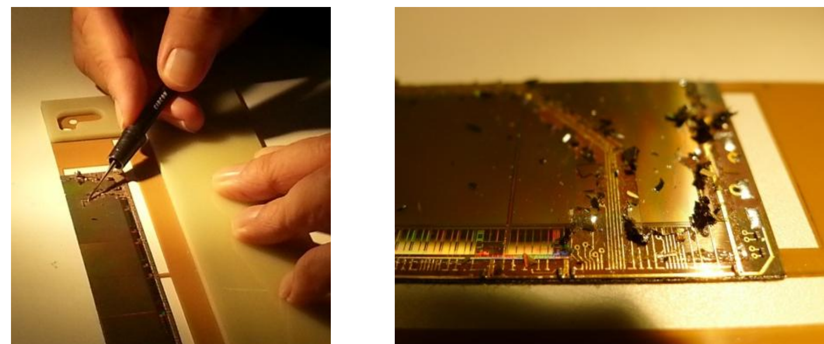
Hole/crack caused by high pressure on dust

Lessons learned - *2*



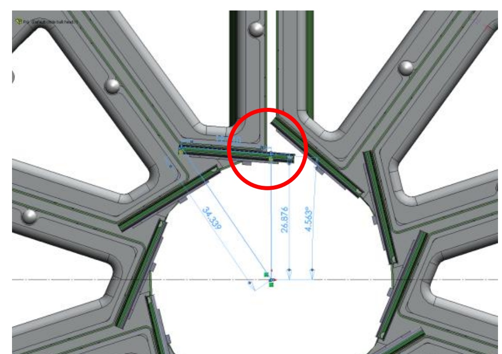
Sensor IR picture overlayed with diagrams

4. 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



Flawed ladder dissection: searching for shorts

5. 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: ~ 2.7 cm inner radius



Inner layer design

Lessons learned - 3

- PXL Engineering Run assembly crucial to deal with a large number of unexpected issues
- Assembly procedure refined and effective tools for troubleshooting ladders developed on the basis of this experience

ER ladder quality assessment *(03/20/2013)*	**#**	**%**
Fully operating ladders	15	55.6
Lower quality operating ladders *(>8 operating chips)*	4	14.8
Recoverable not operating ladders *(need fix or workaround)*	4	14.8
Dead ladders *(not recoverable)*	4	14.8
Total	**27**	**100.0**

- Goal for the final PXL detector: ladder construction yield close to ~100%

Final PXL Detector Production Status

- **36 ladders assembled**
  - Fully functional sensors
  - Cu low-mass cable, new design including solder mask on both sides
    - Al low-mass cable delivery delayed to mid September, expected for the inner layer
- **96% assembly yield** over the tested ladders
  - 24 Ladders completed, ready to be assembled on sectors
- MTB Electronic Boards being redesigned
- Production Firmware major upgrade
- Detector control software optimized

Summary and Outlook

- **Engineering Run PXL Detector** successfully assembled and installed in STAR
  - Many unexpected production **problems discovered and corrected**
  - **Insertion and readout chain** fully validated
  - Preliminary results from collected data show **good matching with TPC tracks**
- The **Production PXL Detector** is now coming together:
  - **Primary detector** to be installed by December 2013
  - **Spare detector** to be delivered to BNL by beginning 2014
  - Additional single **spare ladders** to be assembled by Spring 2014
- First **Production Data** expected for **Jan/Feb 2014**

Thank you for your attention!

Spare Material

Design Specifications

Pointing resolution	(12 ⊕ 19 GeV/p·c) μm
Layers	Layer 1 at 2.7 cm radius Layer 2 at 8 cm radius
Pixel size	20.7 μm X 20.7 μm
Hit resolution	6 μm
Position stability	6 μm rms (20 μm envelope)
Radiation length per layer	X/X_0 = 0.37%
Total sensitive area	0.15 m^2
Number of pixels	356 M
Frame 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

Radiation Length of active area

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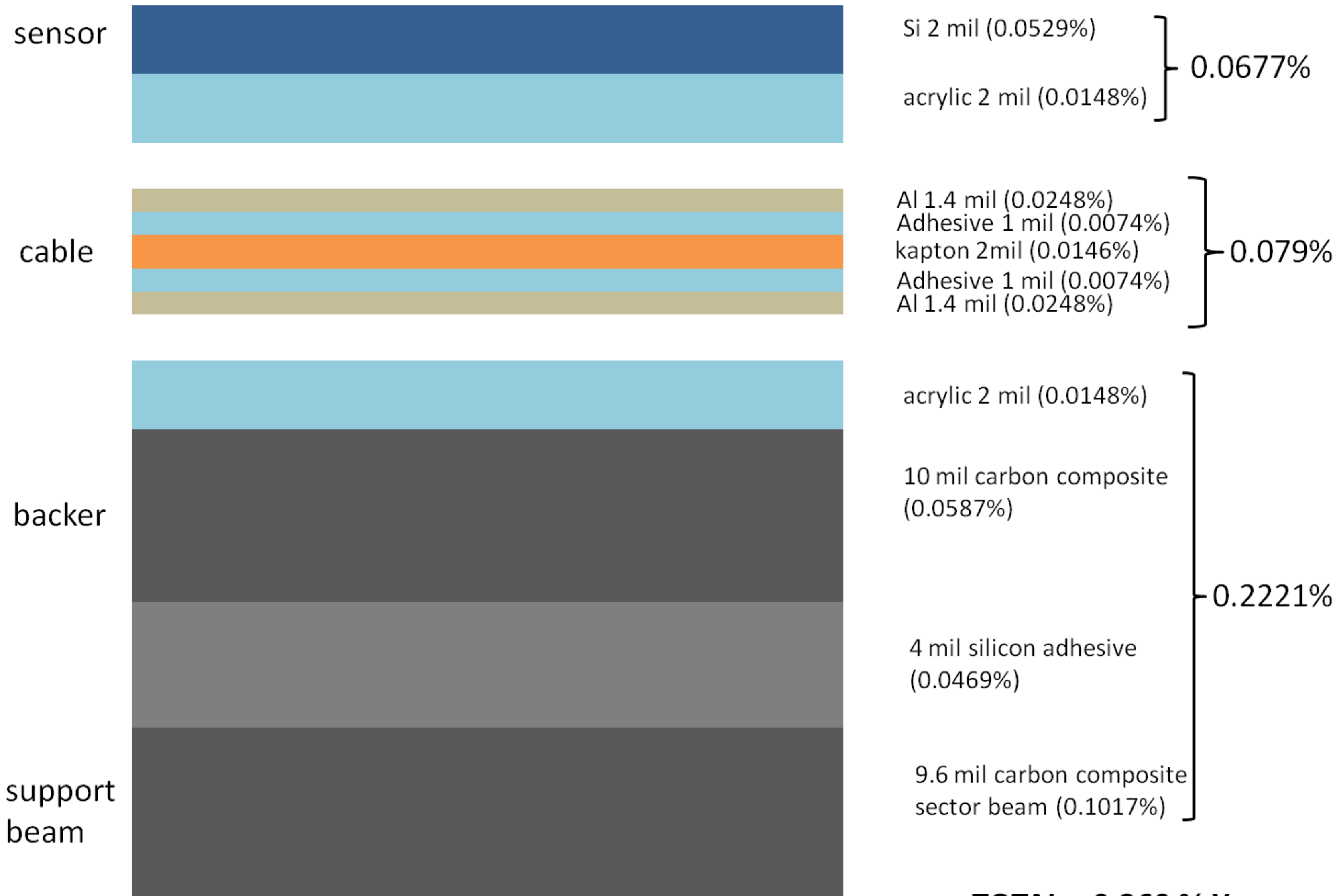
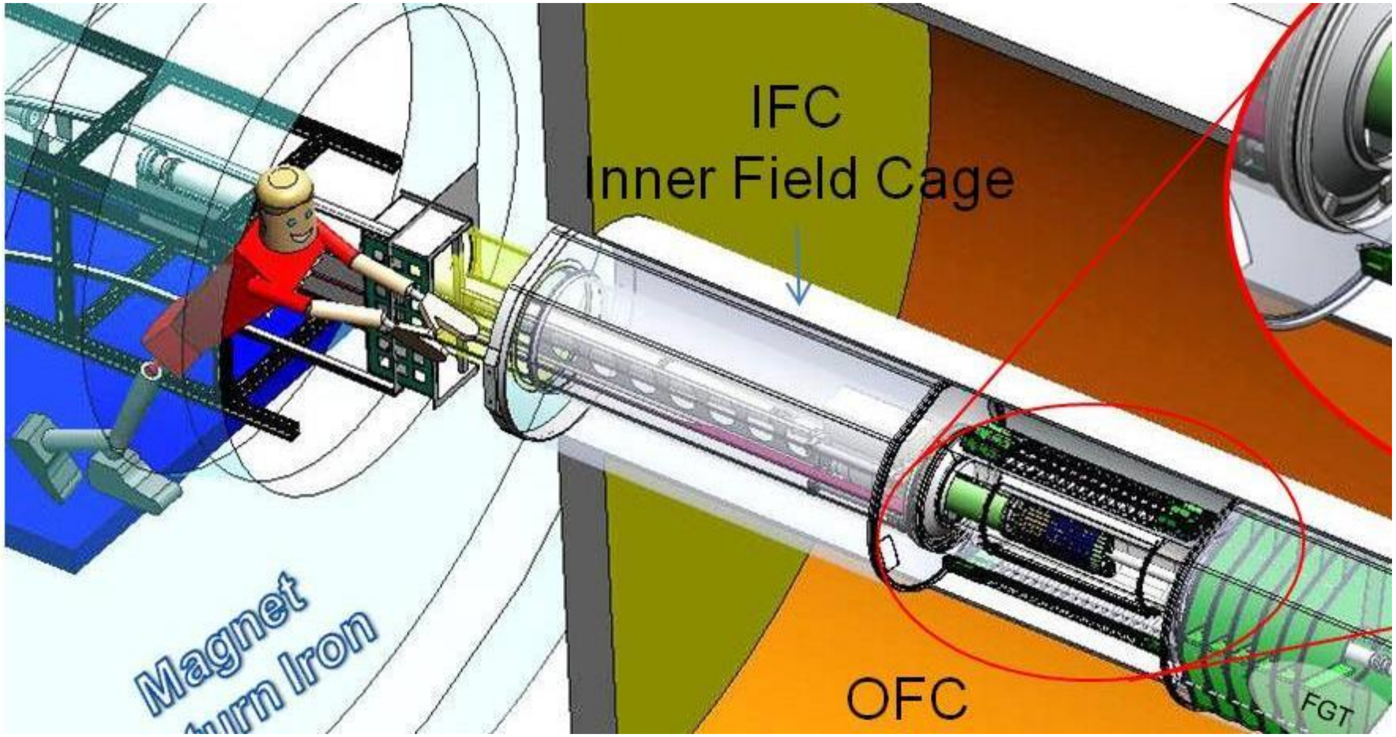


TOTAL = 0.369 % X_0

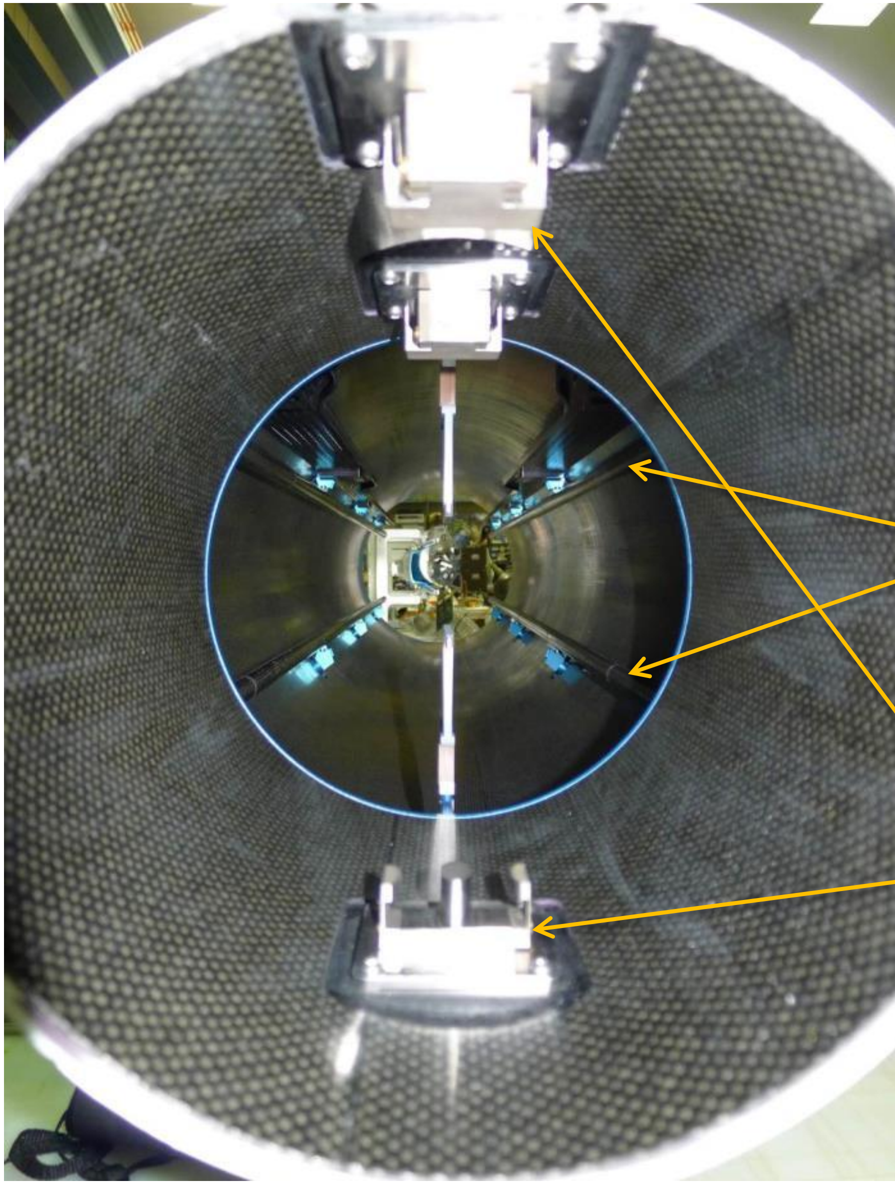
NOTE: Does not include sector tube side walls

PXL detector – insertion mechanics



- Unusual mechanical approach.
- Cantilevered and insertable (1 day)
- Pre-surveyed and mechanically stable to a level that preserves the survey.
- Detector inserts and initiates a clamshell closing around beam pipe, and is locked into position on kinematic mounts.

PXL insertion mechanics



Interaction point view of the PXL insertion rails and kinematic mount points

Carbon fiber rails

Kinematic mounts