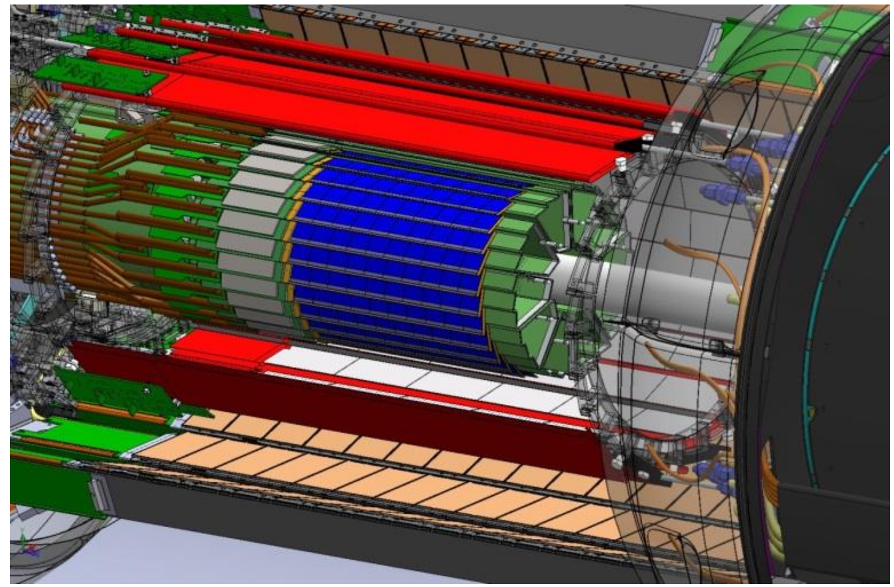
Upgrade of the STAR silicon detectors

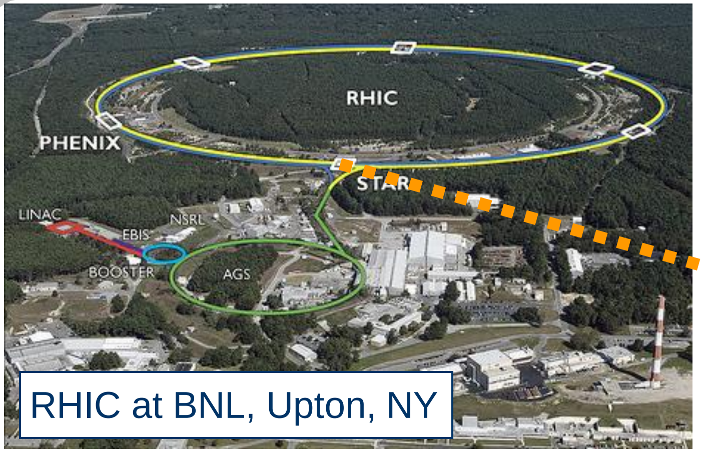


Michal Szelezniak for the STAR collaboration

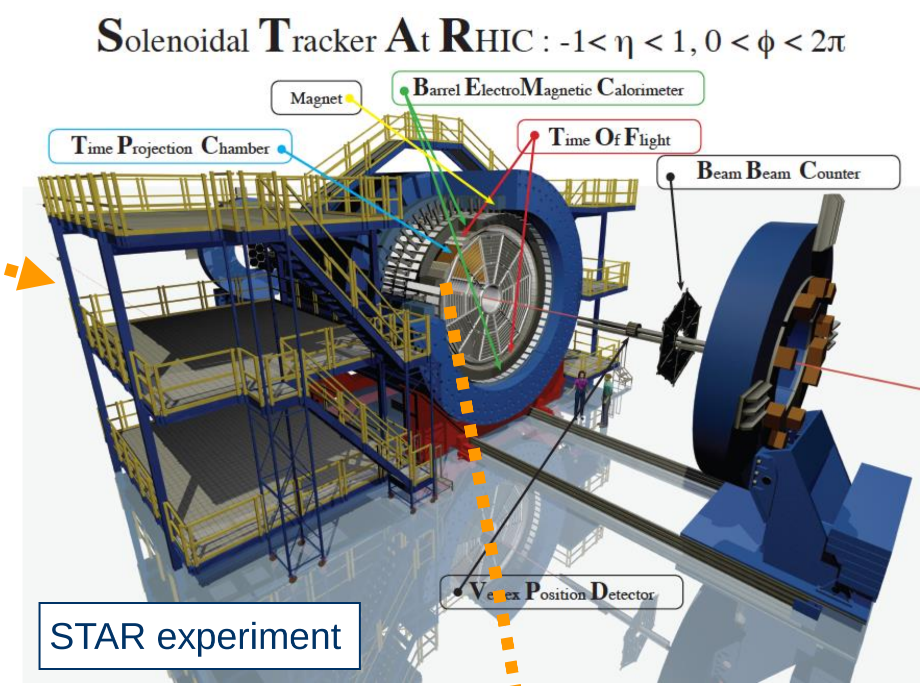
Institut Pluridisciplinaire Hubert Curien (IPHC-CNRS), Strasbourg, France

STAR HFT

Outline

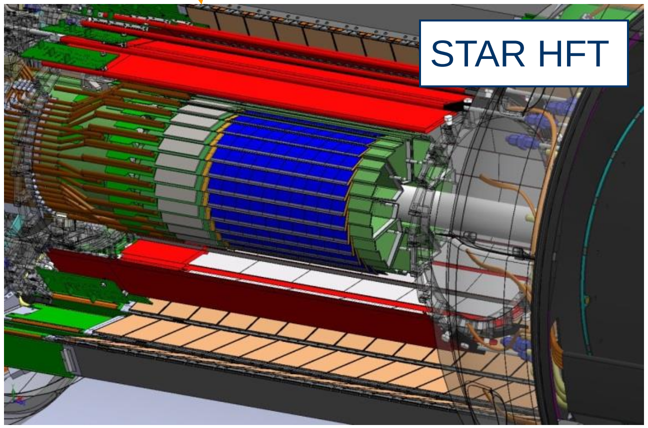


RHIC at BNL, Upton, NY



STAR experiment

- STAR HFT
  - 3 sub-detectors
- PXL Detector
  - First MAPS based vertex detector
- HFT status and performance
- PXL detector – Lessons Learned
- Summary and Outlook

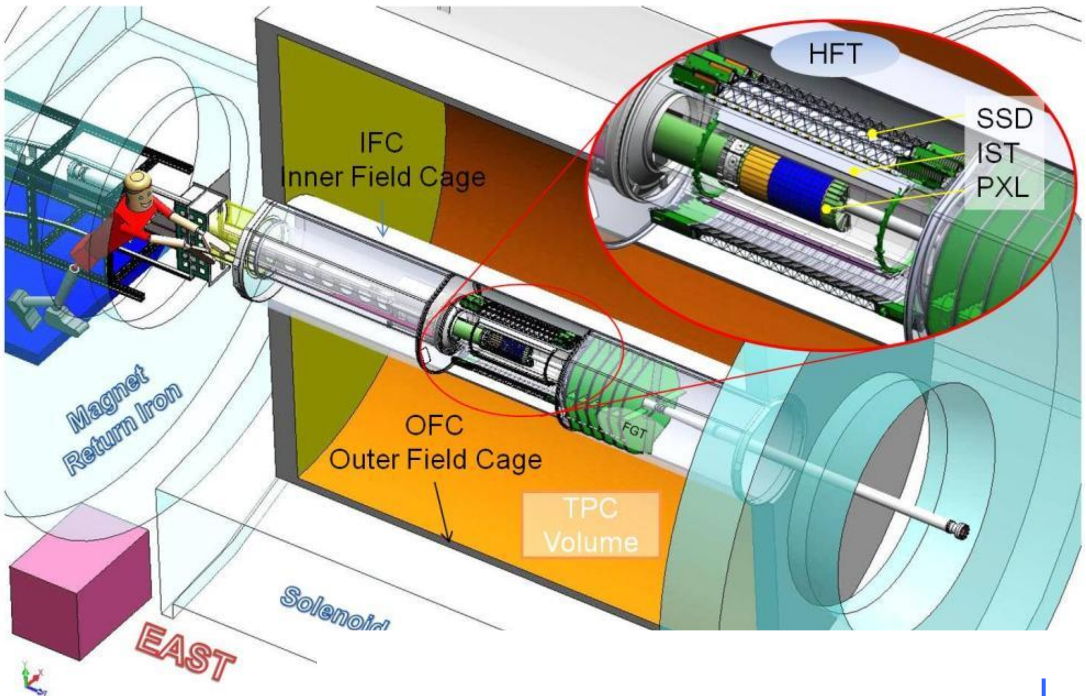


STAR HFT

STAR HFT

STAR Heavy Flavor Tracker (HFT) Upgrade

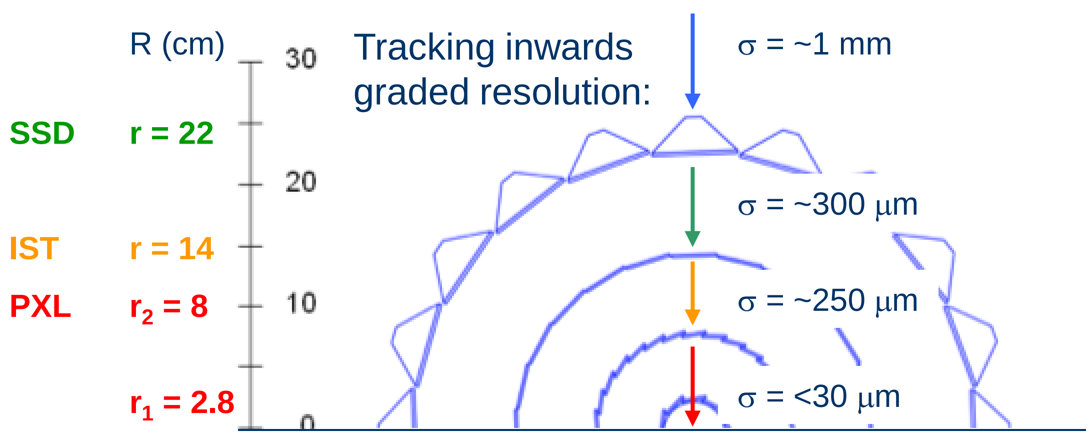
- Built to identify mid rapidity Charm and Beauty mesons and baryons through direct reconstruction and measurement of the displaced vertex with excellent pointing resolution.



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

HFT – Heavy Flavor Tracker

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

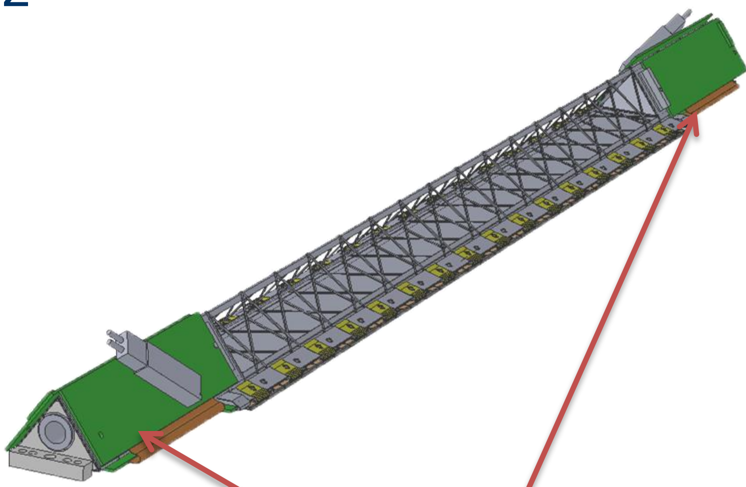


Silicon Strip Detector (SSD)

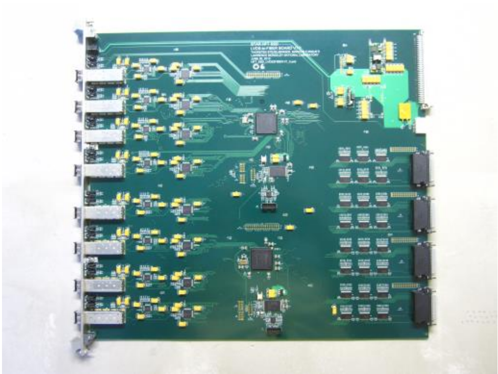
- Double sided silicon strip modules with 95 µm pitch
- Existing detector with new faster electronics
- Radius: 22 cm
- Radiation length 1% X_0

SSD refurbishment

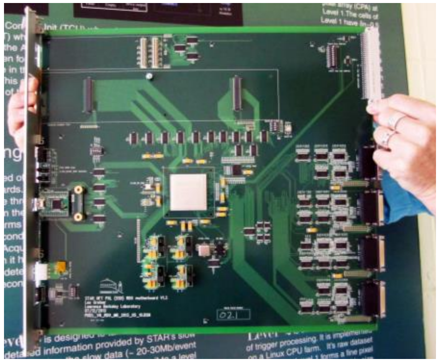
- 20 ladders from the old SSD detector
- Upgrade readout from 200 Hz to 1 kHz
- New
  - 40 ladder cards on detector
  - 5 RDO cards
  - 5 Fiber-to-LVDS boards
  - Upgraded cooling system (air cooled)



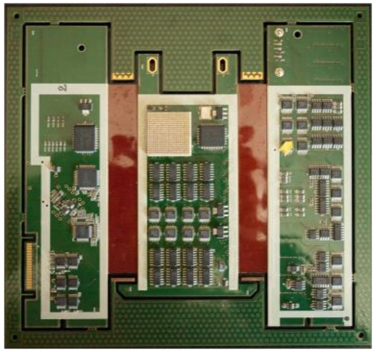
Fiber-to-LVDS



RDO board, adapted from PXL

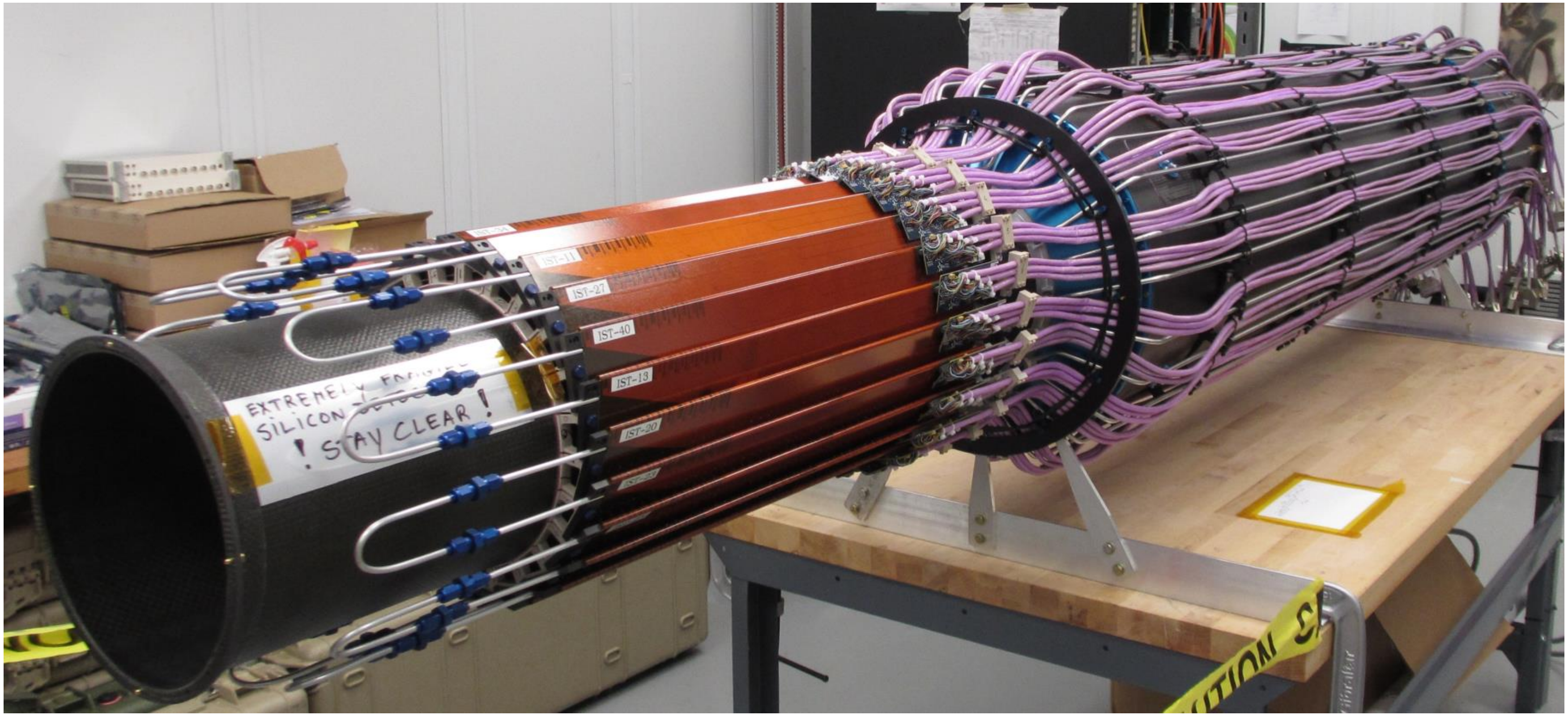


Ladder Cards



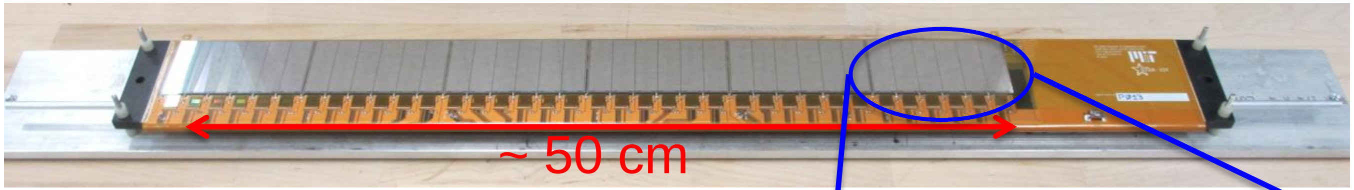
Intermediate Silicon Tracker (IST)

- Single sided double-metal silicon pad with 600 μm x 6 mm pitch
- Radius: 14 cm
- Radiation length <1.5% X_0



- Conventional Si pad detector using CMS APV chip for ladders
- Readout system copy of just completed FGT detector system
  - G. Visser et al. A Readout System Utilizing the APV25 ASIC for the Forward GEM Tracker in STAR, IEEE Real Time Conference Record, Berkeley, CA, 2012

IST characteristics



ϕ-Coverage	2π
|η|-Coverage	≤1.2
Number of Staves	24
Number of hybrids	24
Number of sensors	144
Number of readout chips	864
Number of channels	110592
r-ϕ resolution	172 µm
Z resolution	1811 µm
R-ϕ pad size	594 µm
Z pad size	6275 µm

IST stave = Carbon fiber ladder
+ Kapton flex hybrid
+ Passive components
+ 6 silicon pad sensors
+ 3 x 12 APV25-S1 readout chips
+ Aluminum cooling tube
+ Liquid coolant (3M Novec 7200)

IST staves were assembled/tested/surveyed at UIC/FNAL and MIT/BNL sites (18 staves produced at each site).

PXL detector

- MAPS sensors with 20.7 µm pitch
- Radius: 2.8 and 8 cm
- Radiation length <0.4% X_0 in inner layer

first MAPS based vertex detector at a collider experiment

PXL characteristics

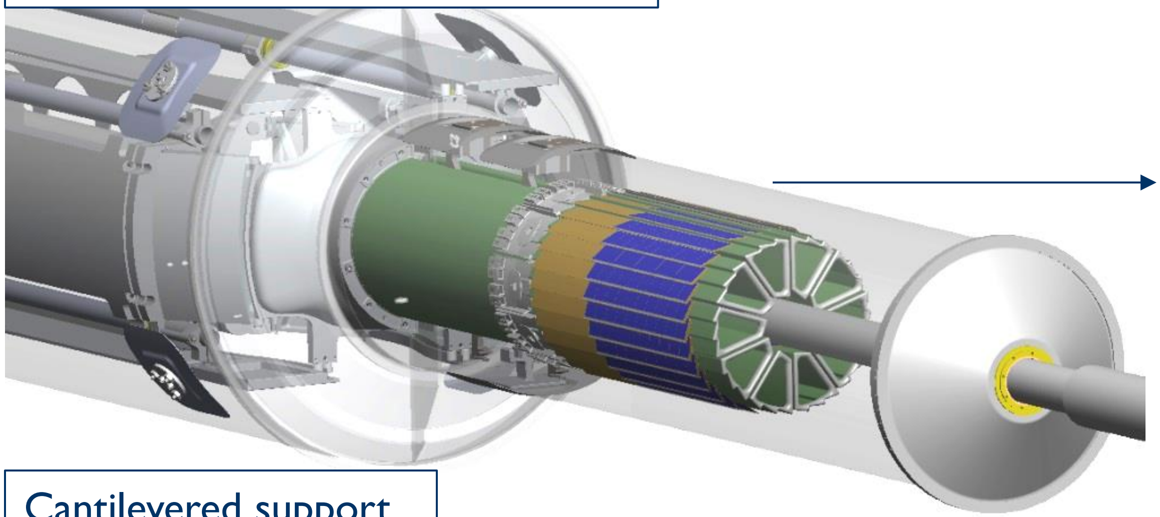
DCA Pointing resolution *	$(12 \oplus 24\ \mathrm{GeV}/p \cdot c)\ \mu\mathrm{m}$
Layers	Layer 1 at 2.8 cm radius Layer 2 at 8 cm radius
Pixel size	20.7 μm X 20.7 μm
Hit resolution	3.7 μm (6 μm geometric)
Position stability	6 μm rms (20 μm envelope)
Radiation length first layer	X/X_0 = 0.39% (Al conductor 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

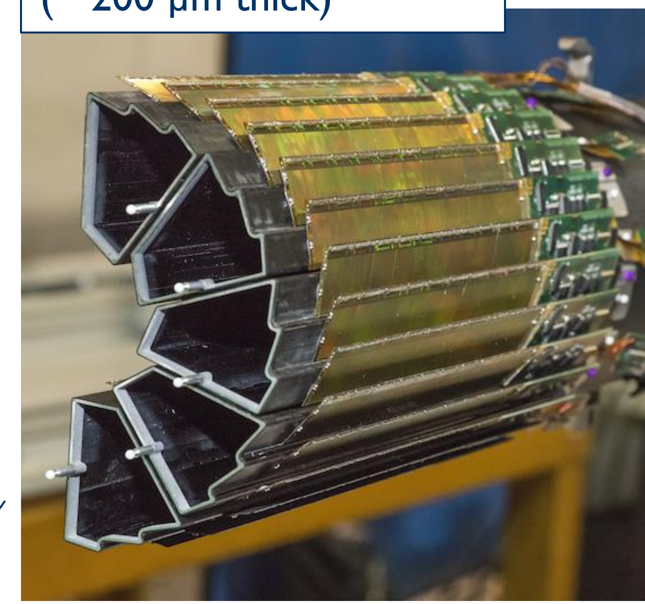
PXL architecture

Mechanical support with kinematic mounts (insertion side)



Cantilevered support

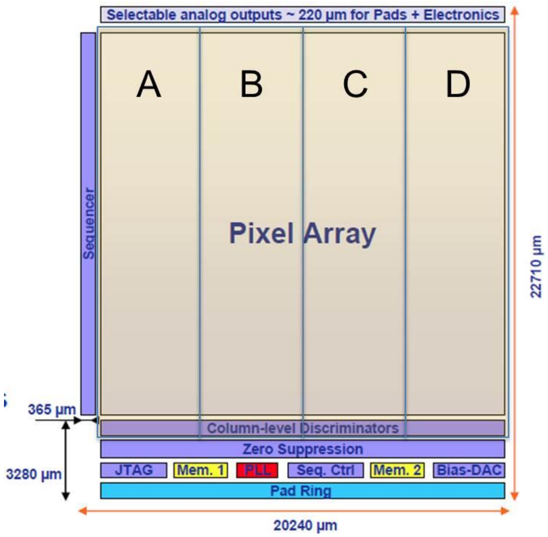
carbon fiber sector tubes (~ 200 μm thick)

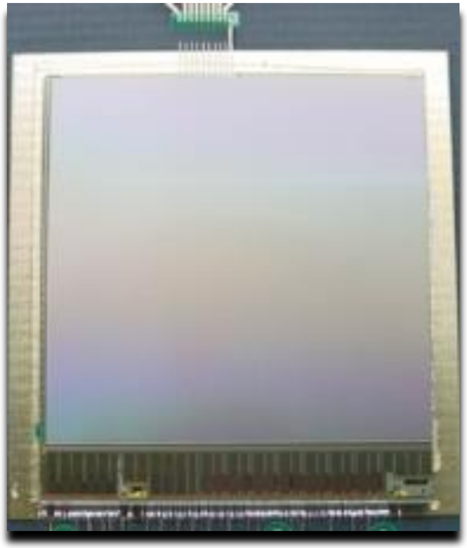


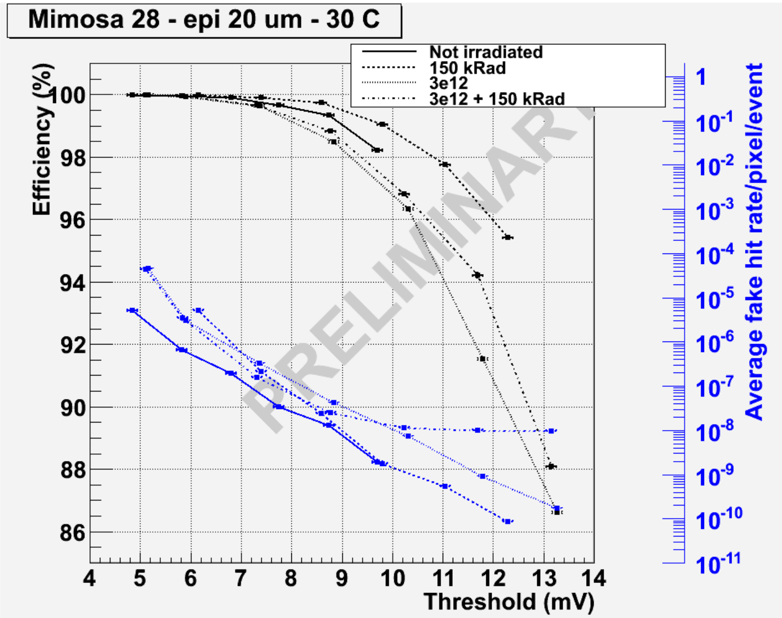
Ladder with 10 MAPS sensors (~ 2×2 cm each)

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

PXL detector Ultimate-2 sensor





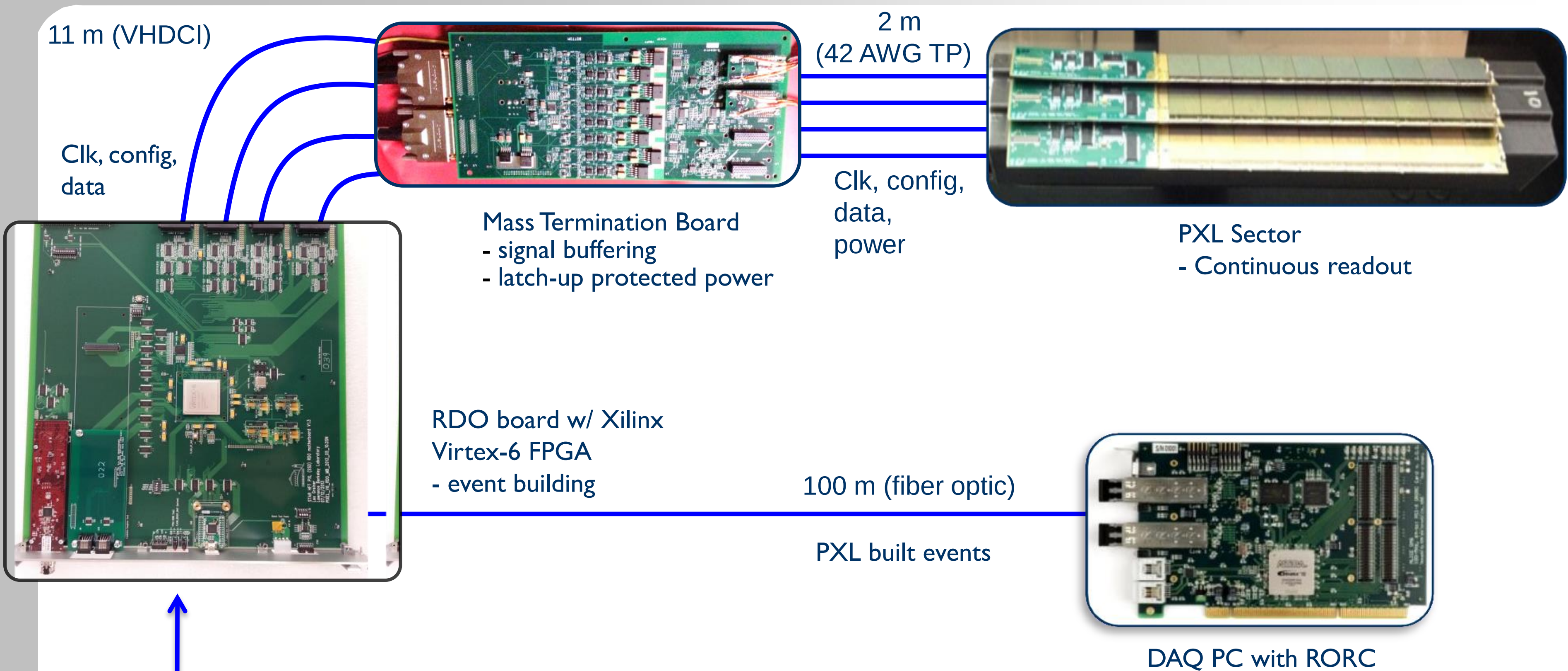


3rd generation sensor developed for the PXL detector by the PICSEL group of IPHC, Strasbourg

- 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

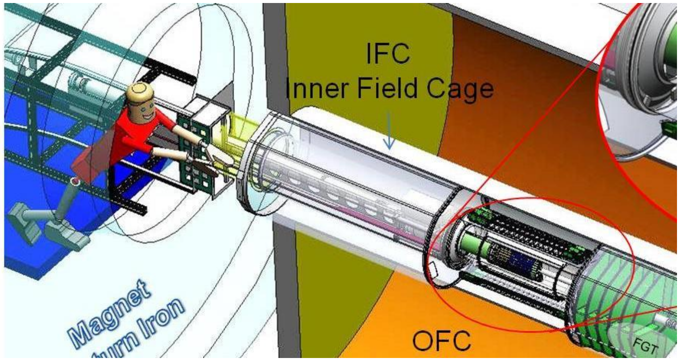


Highly parallel system

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

PXL insertion

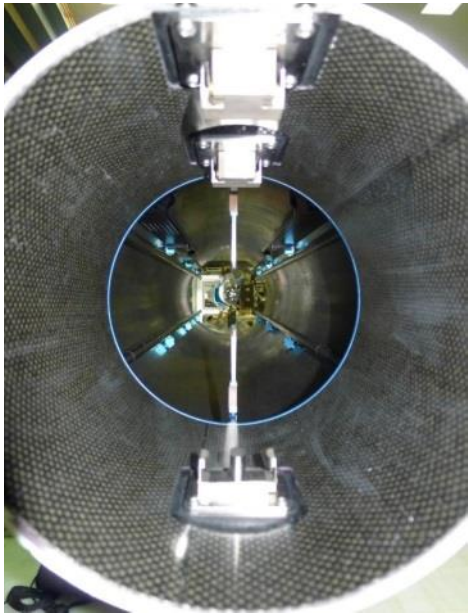
Yes – we push it in by hand



Unique mechanical design:

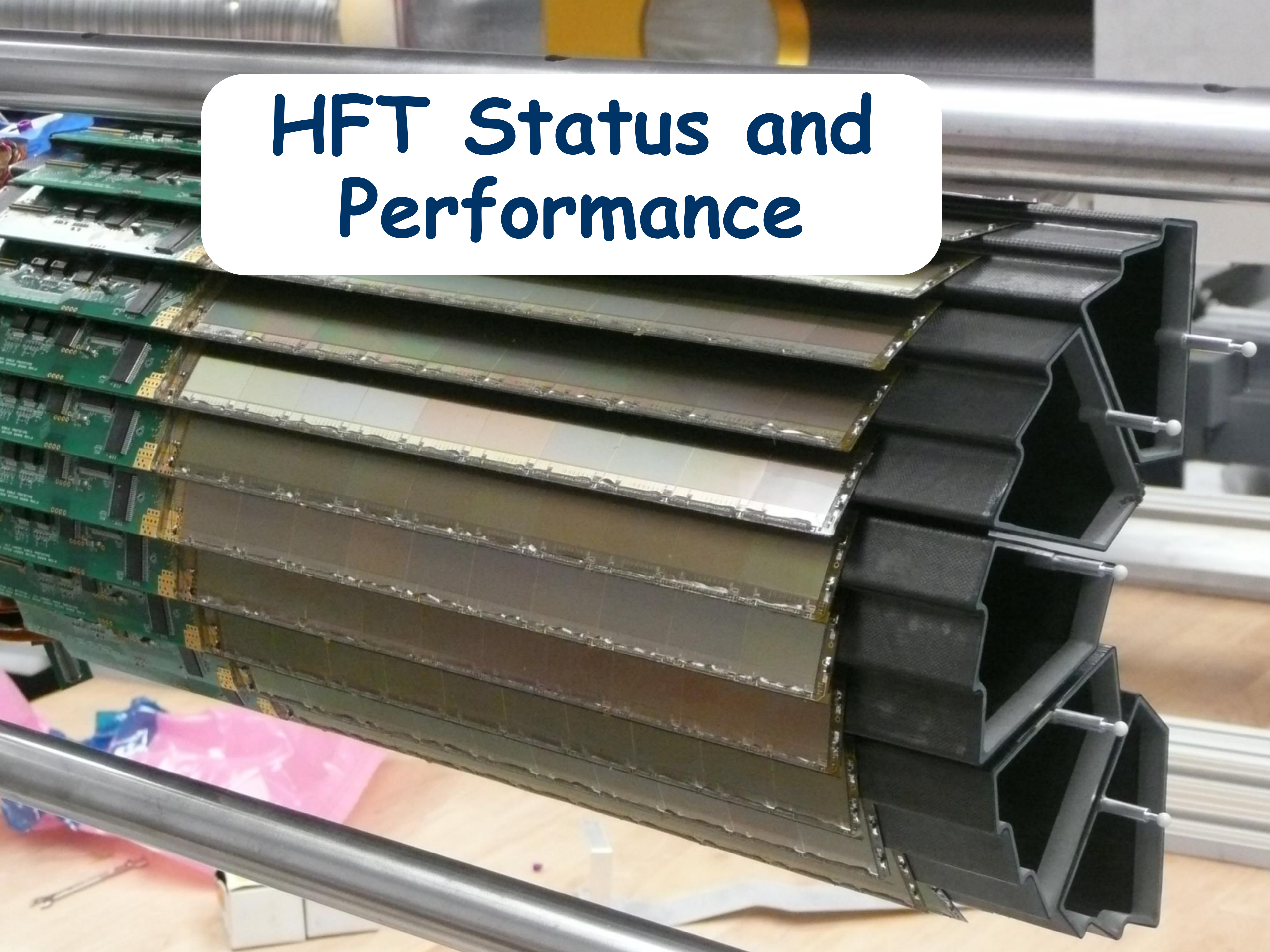
- detector is inserted along rails and locks into a kinematic mount on the insertion end of the detector
- Allows for rapid (1 day) replacement with a characterized spare detector

Kinematic mounts



Insertion of PXL detector

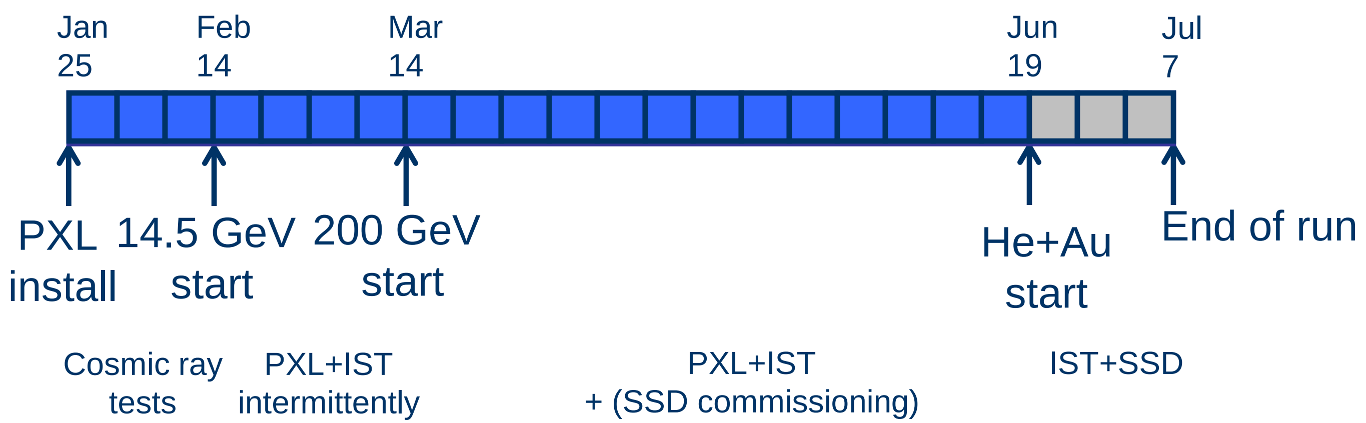
HFT Status and Performance



STAR HFT

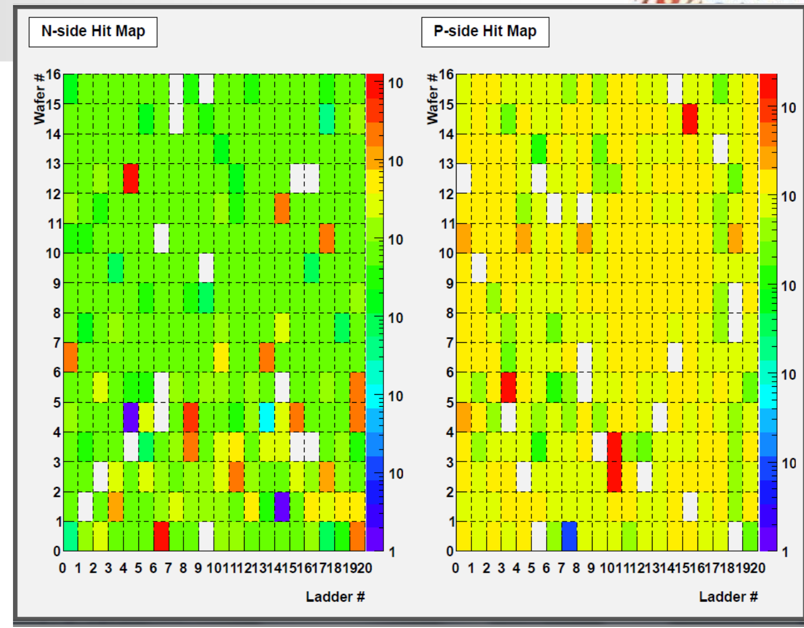
HFT Status

- IST, SSD installed into STAR in the fall 2013
- PXL inserted into STAR at the end of January 2014
- Commissioning of HFT detectors in February and March including Cosmic Ray data taking (extended SSD commissioning)
- Physics data taking March - July
- Collected >1.2 Billion events

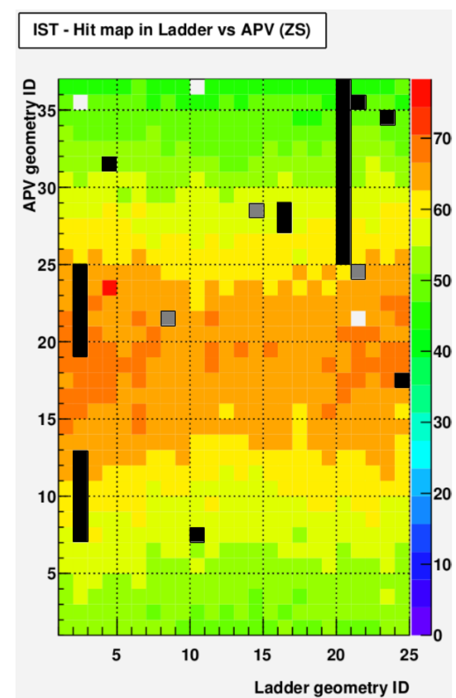


HFT Status

- SSD
  - The RDO runs at <20% dead-time at 1 kHz
    - The ultimate limit is due to old Si modules (circa 2000)
  - 6% dead wafers
  - 90 % of the strips are active in the remaining wafers
  - Collected 172 M Au+Au events and 57 M He3+Au events



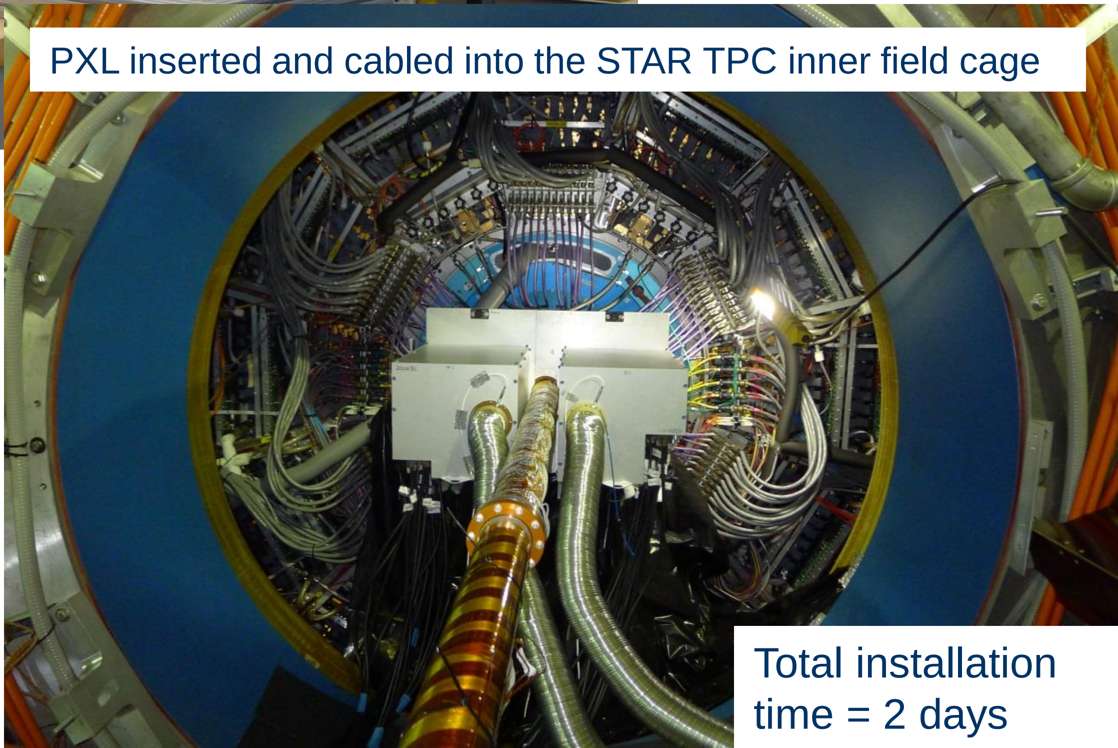
- IST
  - 864 readout chips and 110592 channels total
  - More than 95% fully functional channels
  - Hit efficiency ~99%
  - S/N 15:1-30:1
  - Coolant leak rate 0.5-1.0% per day (to be fixed)
  - Participated in data taking for He3+Au collisions



PXL installation

At installation:

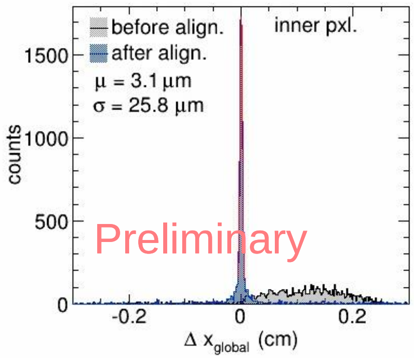
- PXL installed with all 400 sensors working, <2k bad pixels
- 38 ladders with Cu flex + 2 inner ladders with Al flex
- Noise rates were tuned for ~1.5 x 10^{-6} per sensor for most sensors

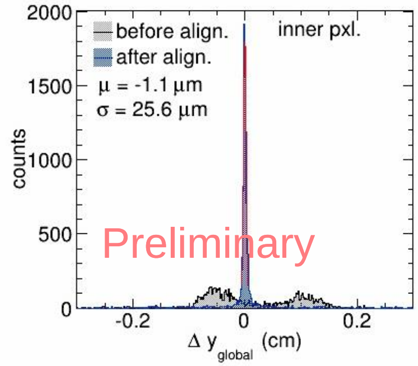


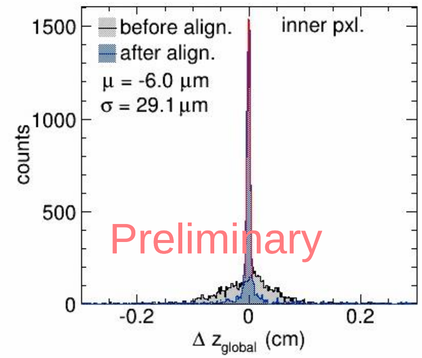
STAR HFT

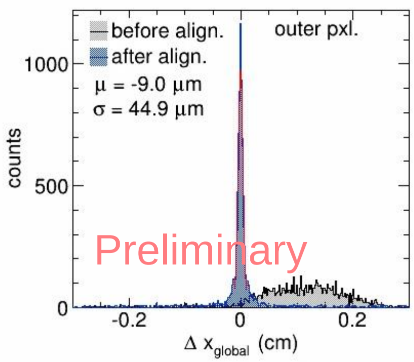
PXL preliminary half-to-half pointing residuals

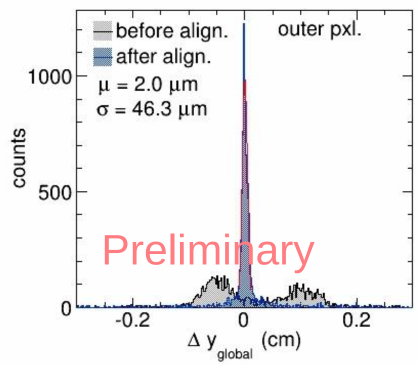
- PXL hit residual distributions before and after PXL half-to-half alignment (analysis by A. Schmah, LBL)

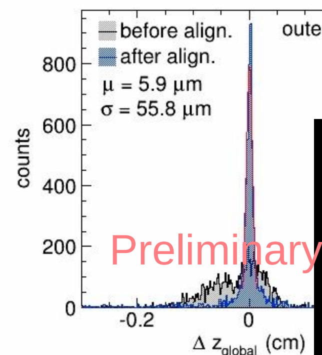




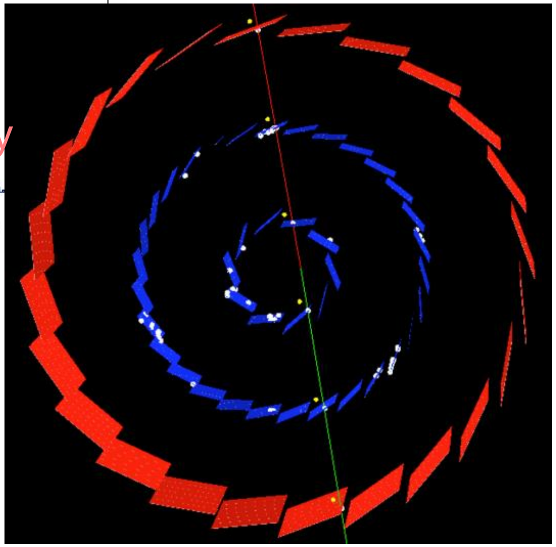








Cosmic ray event (PXL + IST)



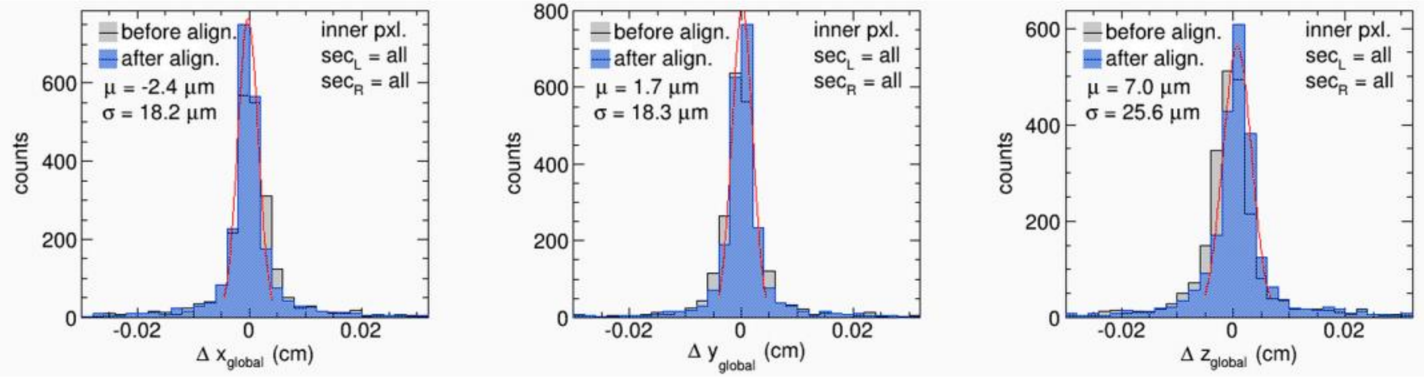
- Consistent with expectations for alignment and momentum of muons
- σ ~ 25μm for inner layer and 50μm for outer layer

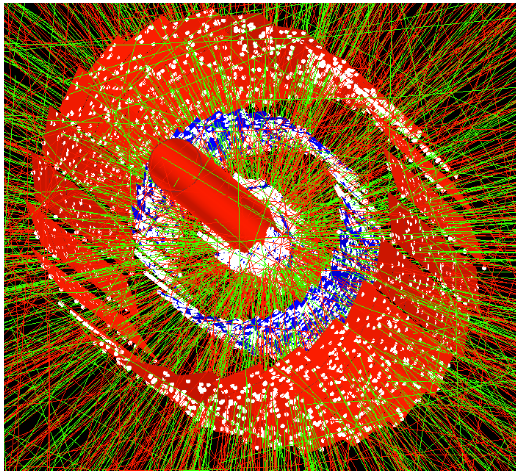
Preliminary DCA Pointing resolution

- result from the STAR HFT software group

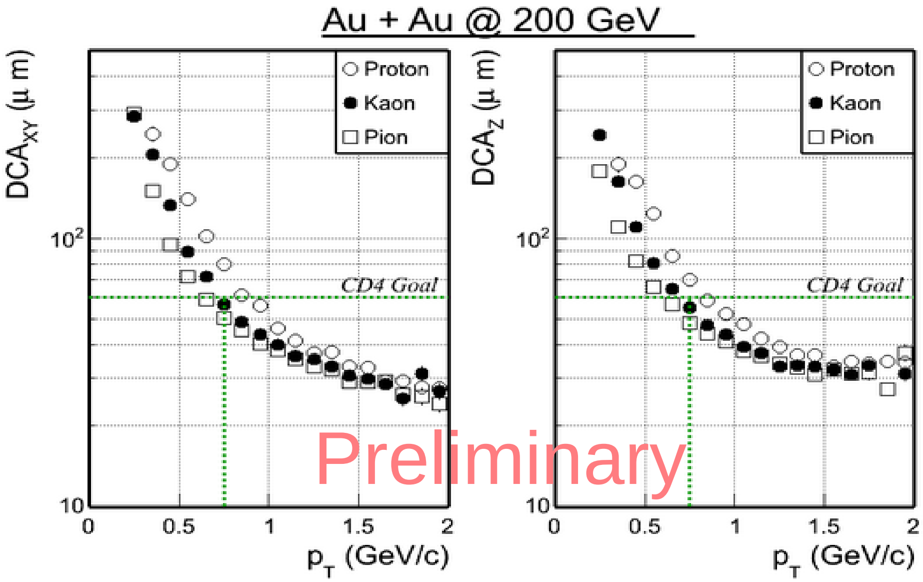
PXL preliminary half-to-half pointing residuals after sector alignment

- σ < 25 μm for inner layer.





200 GeV Au+Au event

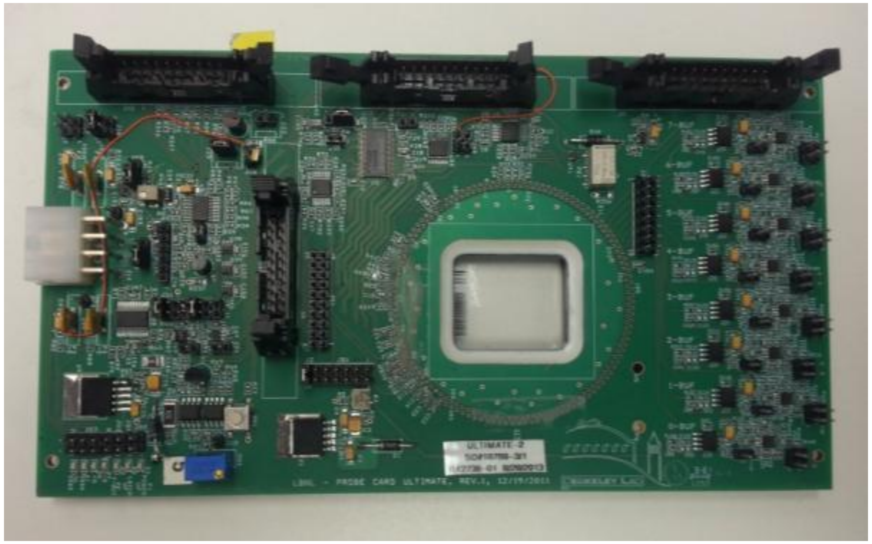


- DCA resolution (TPC + IST + PXL) ~ 30 μm at high p_T (better alignment in progress)
- CD-4 requirement for DCA resolution: 60 μ m for kaons with p_T = 750 MeV/c

PXL Detector Lessons Learned

Probe testing

- Thinned and diced 50 µm thick sensors
- Custom made vacuum chuck
- Full sensor characterization (~15 min):
  - Parameter characterization at different bias V (@ 2.9V, 3V, 3.3 V)
  - I/V measurements
  - Bias optimization
  - Temporal noise and FPN measurements
  - Accidental hit rate scan
  - Response to LED pulse (@ 3.3V)
- Full speed readout @ 160 MHz
- Automated interface to a database



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

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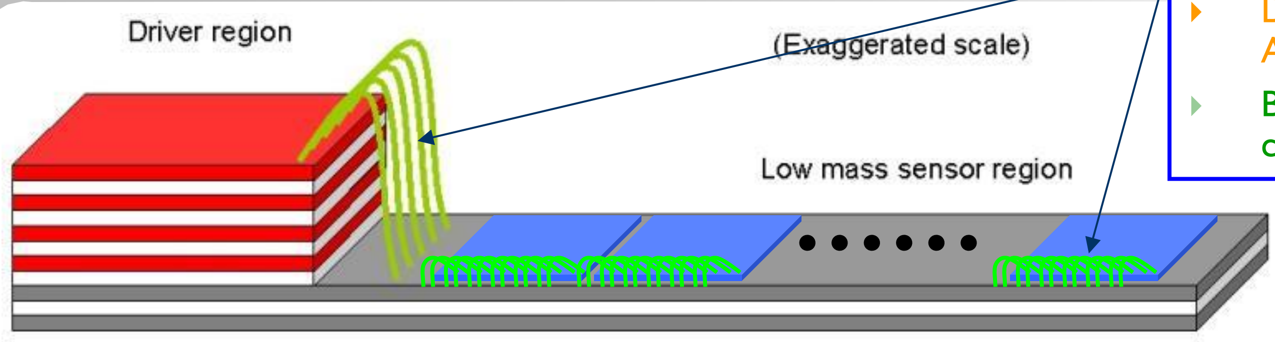
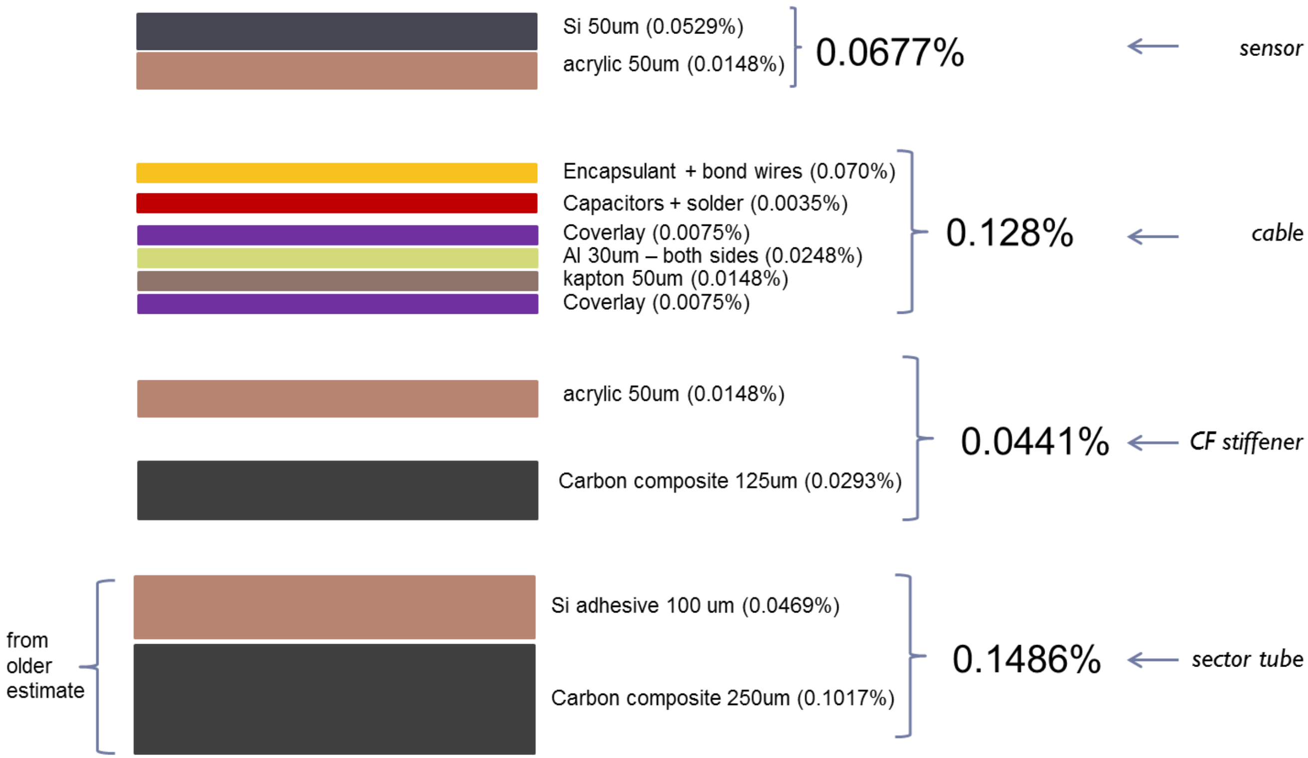
PXL ladder

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

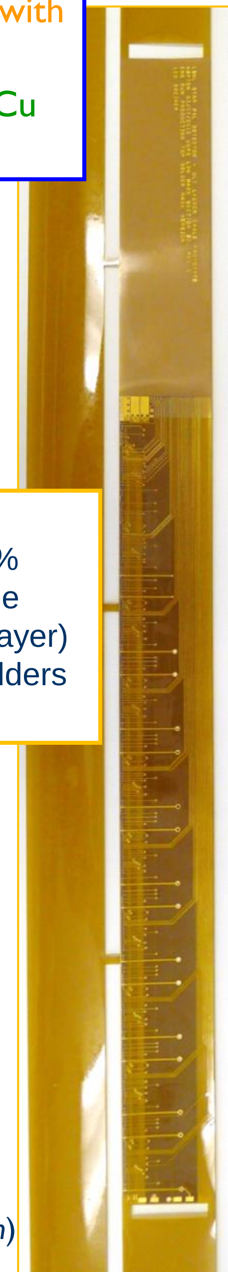




Total = 0.388%

NOTE: Does not include sector tube side walls

Cu conductor:
$X/X_0 \uparrow$ to 0.129% (corrected for the thinner copper layer)
$\Rightarrow$ Cu based ladders X/X_0 = 0.492%



Flex cable
(*Copper version*)

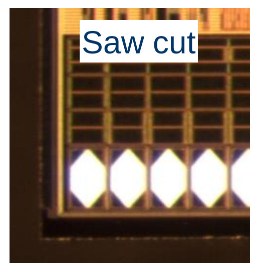
STAR HFT

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
  - Proposed by IPHC in order to improve sensor abuttal

DRIE trenches



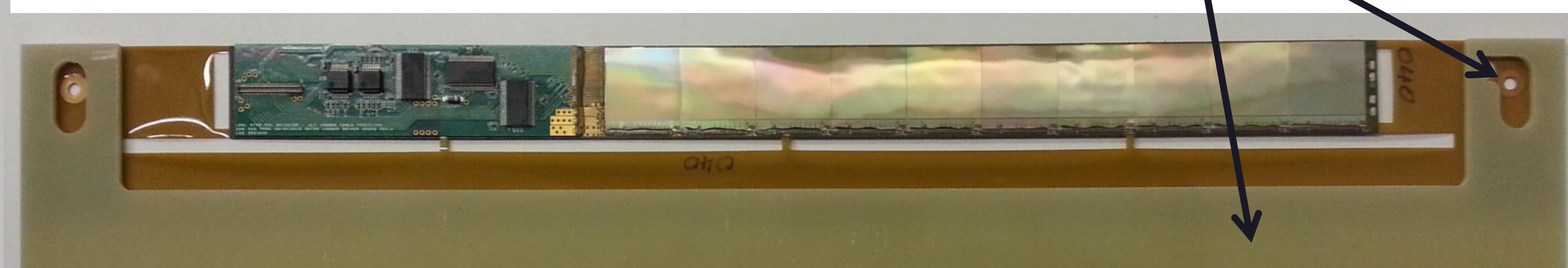
Saw cut

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

Cable reference holes for assembly

Assembled ladder

FR-4 Handler



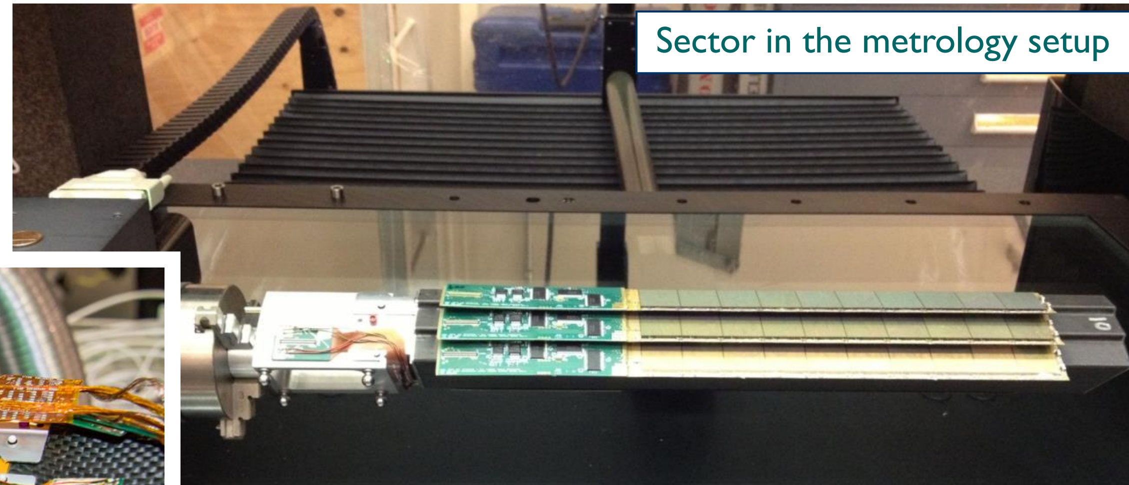
30.5 cm

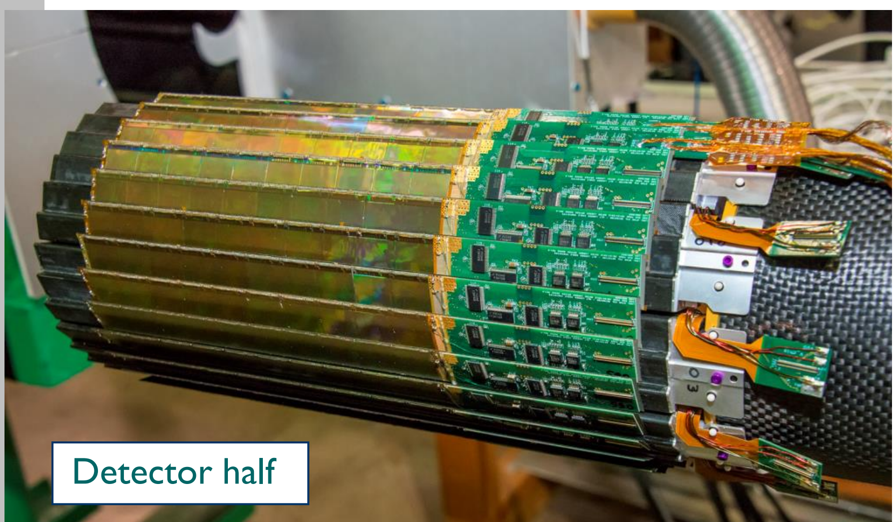
Sector and detector half assembly


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

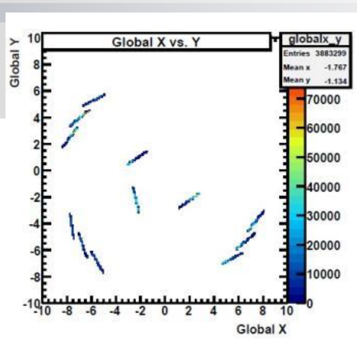
Detector half

- 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)

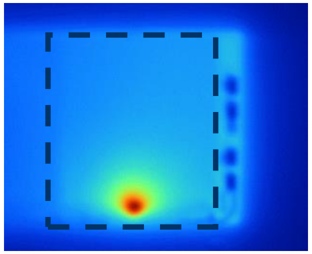
	ladder yield			
	after assembly + bonding	*after encapsulation*	*after sector mounting*	*after metrology*
Tested	92	59	53	48
yield	**0.91**	**0.92**	**0.91**	**1.00**

Engineering run 2013

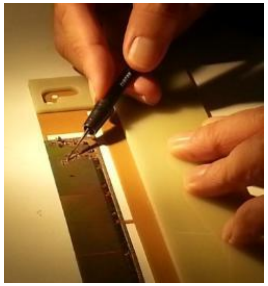


Engineering run geometry

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



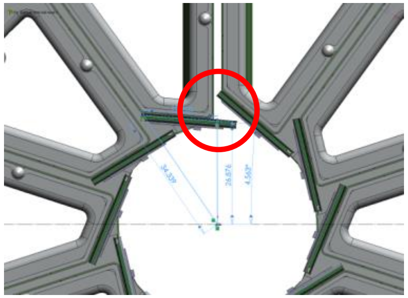
Sensor IR picture



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

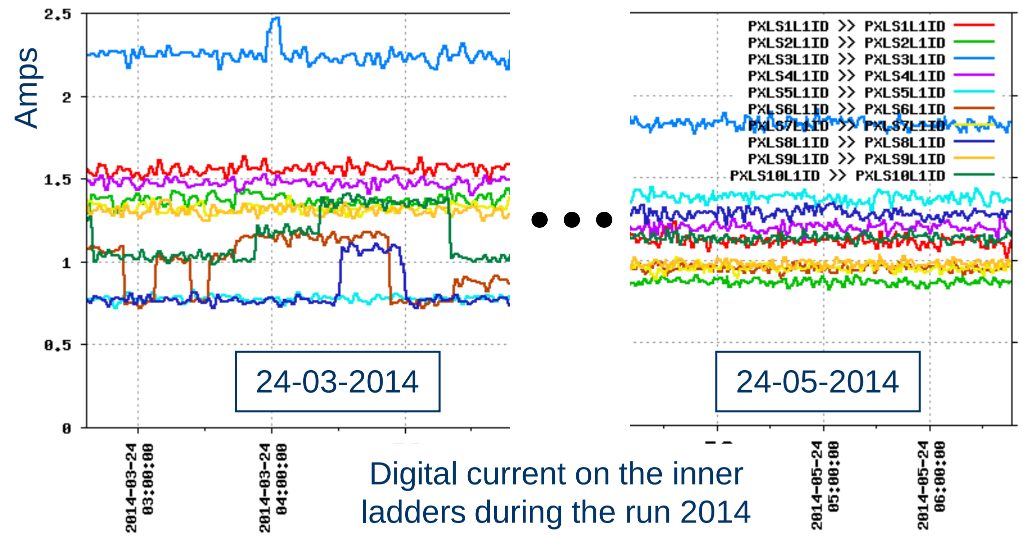
- After the engineering run added functionality to the MTB:
  - remote setting of LU threshold and ladder power supply voltage + current and voltage monitoring

STAR HFT

Office of Science
U.S. DEPARTMENT OF ENERGY

PXL radiation damage in run 2014

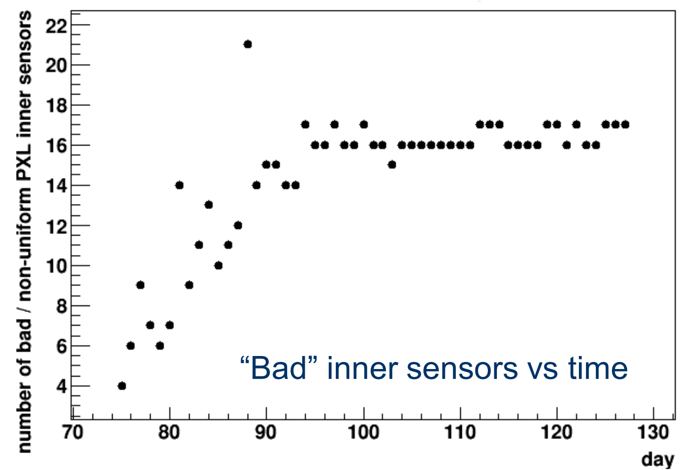
- First damage observed in the 14.5 GeV running after several beam loss events
- continued into 200 GeV run
- Appears to be radiation related (possibly latch-up events):
  - increased digital current, damaged JTAG registers, loss of sub-arrays, etc.
  - mostly in inner ladders (14% of inner layer, 1% 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

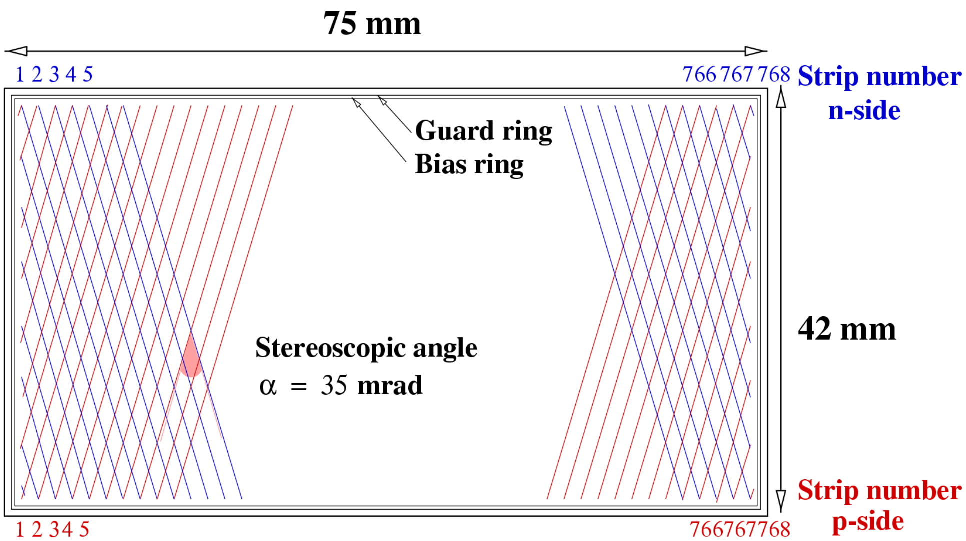
- SEE tests were performed with earlier prototypes, not the production ones
- Operational methods seem to halt radiation induced damage
- Second detector will be protected from day one

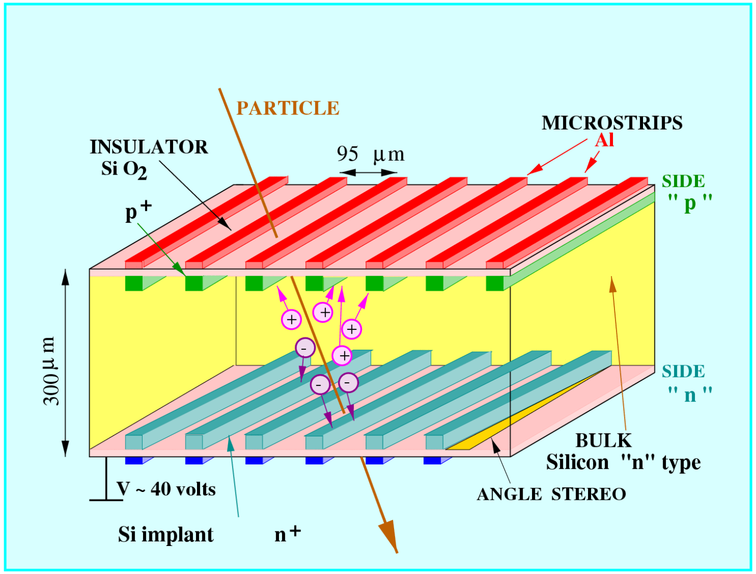
Summary and Outlook

- STAR Heavy Flavor Tracker was installed and commissioned for the 2014 Au+Au RHIC run
- The (preliminary) DCA pointing resolution performance of the installed HFT detectors appears to be as expected and meets the design goals
- Observed radiation related damage in the PXL detector appears to be halted by using operational methods
- The spare detector (with Al conductor cable on the inner ladders) is complete and will be deployed in the next run. We are repairing the damage to the existing detector with the spare ladders.
- DOE CD-4 review is complete and the HFT upgrade meets all of the construction project performance parameters.
- **MAPS appear to be working well as a technology for vertex detectors**
- The PXL detector is the first MAPS based vertex detector and as such leads the way for future vertex detectors based on MAPS technology (such as the ALICE ITS, etc.)

- Thank you for you attention

SSD sensors



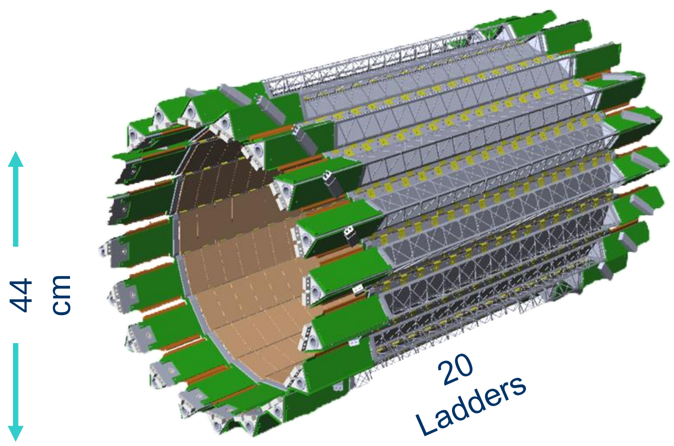


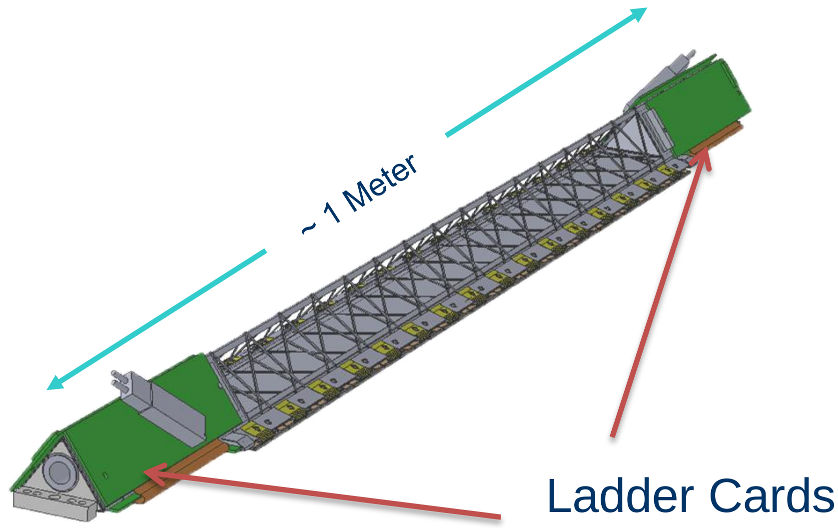
The sensors are double sided strip detectors

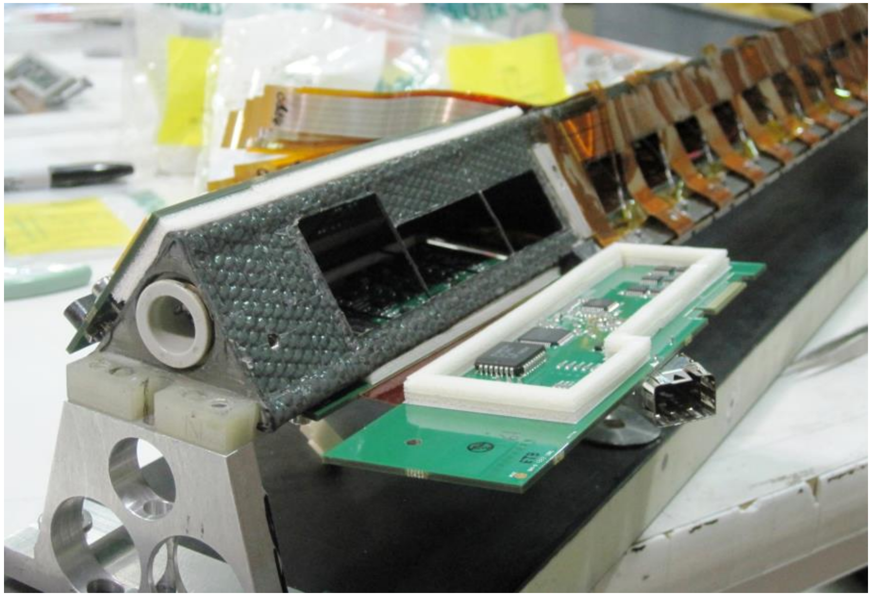
SSD radius	22 cm
SSD length	106 cm
$\vert\eta\vert$ coverage	< 1.2
Number of ladders	20
Number of wafers per ladder	16
Total number of wafers	320
Number of strips per wafer side	768
Number of sides per wafer	2
Total number of channels	491520
Silicon wafer size	75 × 42 mm
Silicon wafer sensitive size	73 × 40 mm
Silicon thickness	300 μm
Strip pitch	95 μm
Stereo angle	35 mrad
R-ϕ resolution	20 μm
Z resolution	740 μm

STAR HFT

Silicon Strip Detector (SSD)







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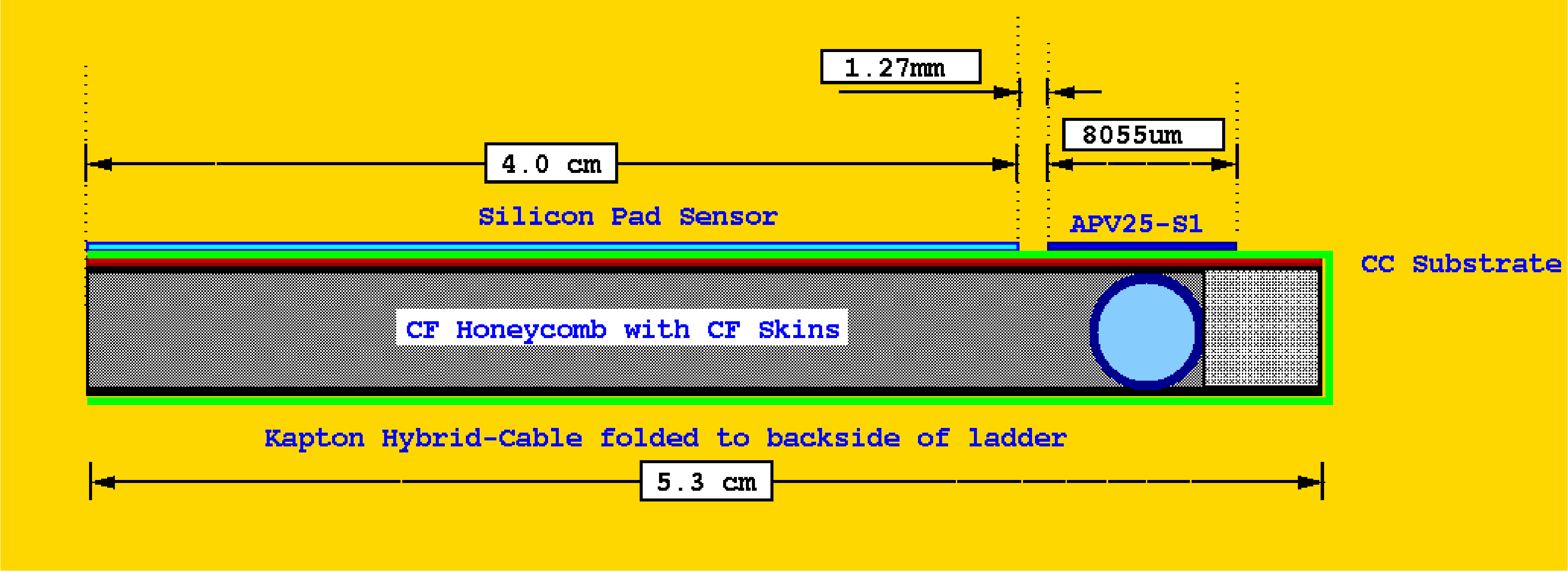
IST Stave


1.27mm
8055um
4.0 cm
Silicon Pad Sensor
APV25-S1
CC Substrate
CF Honeycomb with CF Skins
Kapton Hybrid-Cable folded to backside of ladder
5.3 cm

PXL electronics and operator's GUI

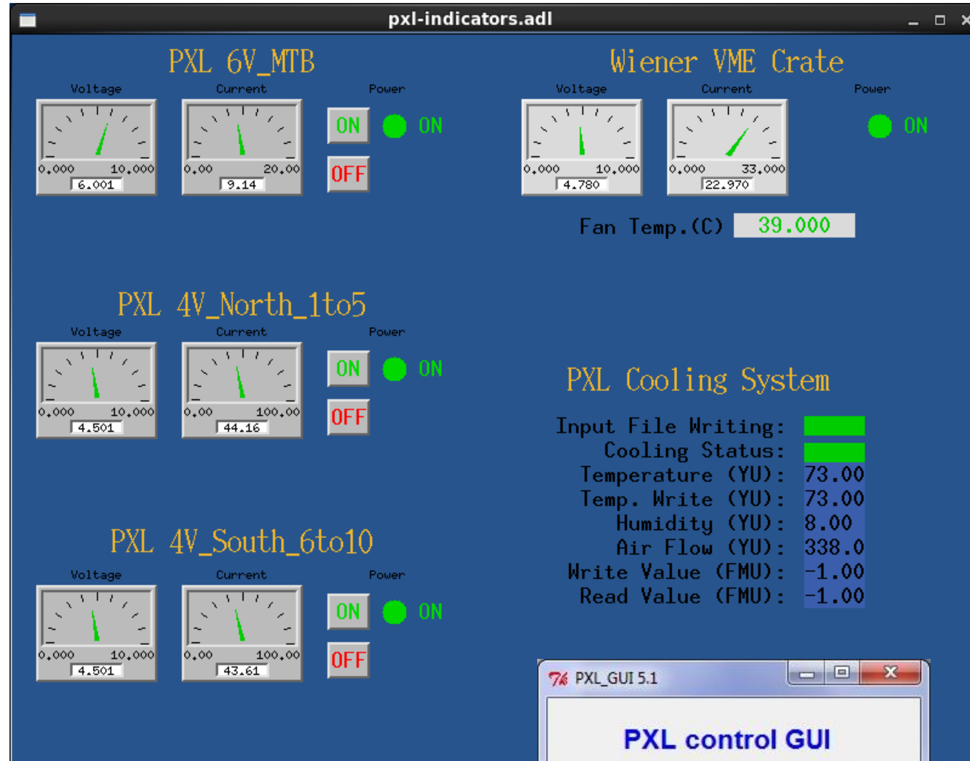
USB hub
USB<->fiber
interlocks

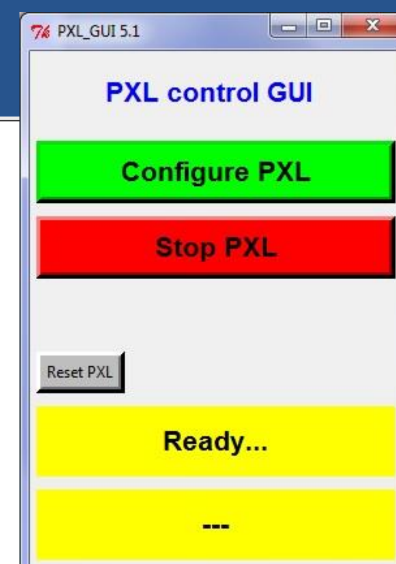
4V South

6V MTBs

4V North

10 RDO boards
1 Trigger
distribution board

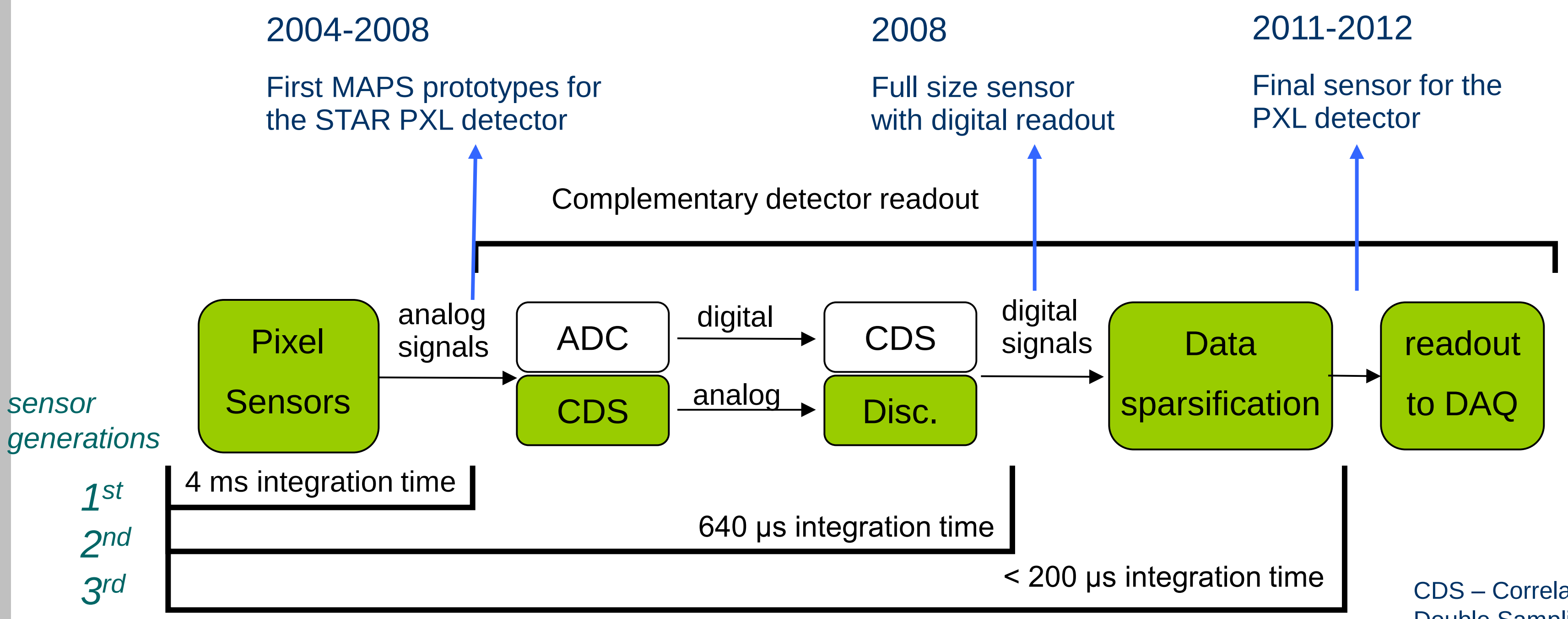




two-panel control interface

PXL sensor development at IPHC

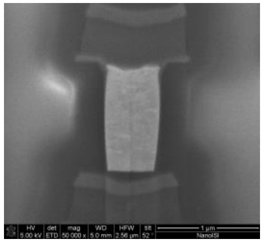
- Three generations of sensors designed specifically for the PXL detector
- PXL sensors benefited from parallel development of multiple other sensor prototypes designed and tested at IPHC



CDS – Correlated Double Sampling

- Finding suitable CMOS technology (AMS0.35)
- Unexpected issues scaling small prototypes to half-reticule size solved by adjustments in the fabrication process

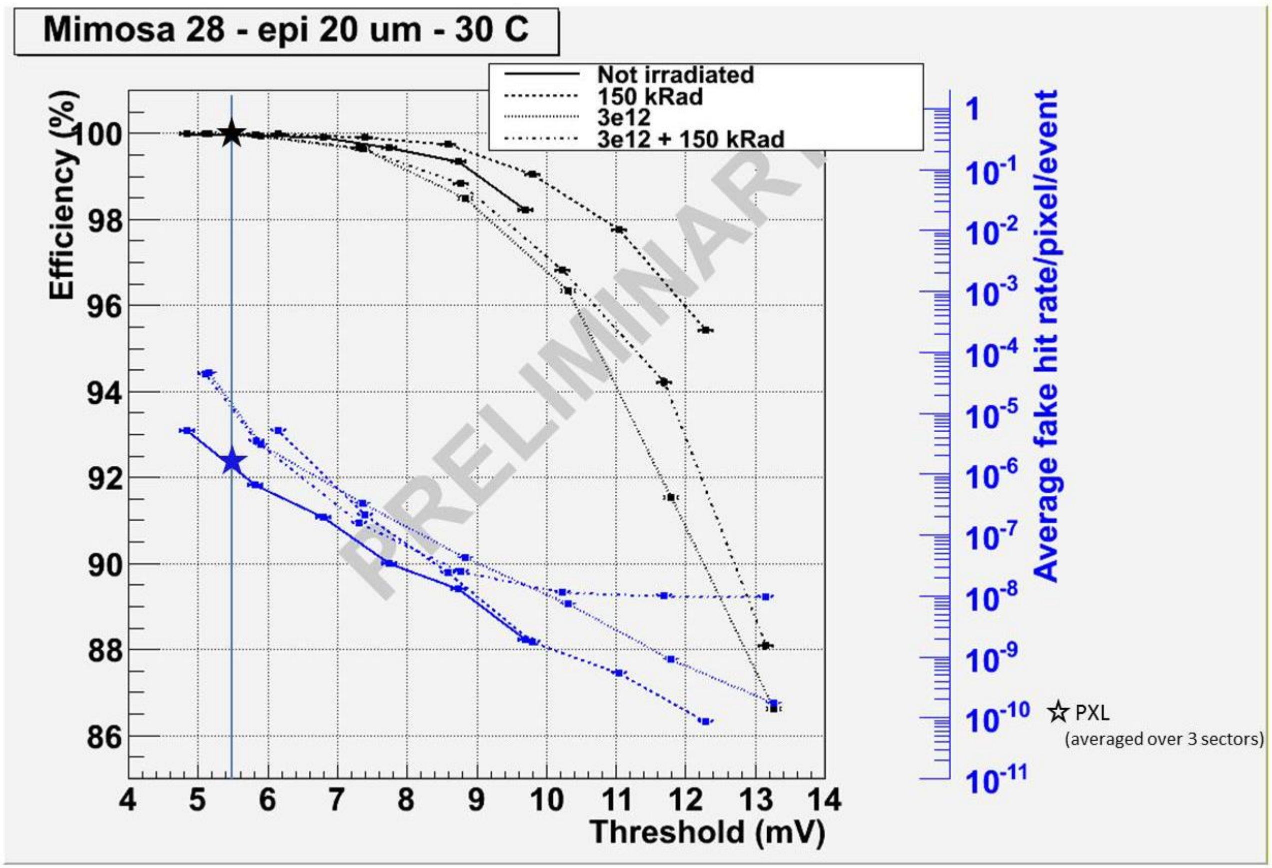
Incomplete via contacts in the middle of the chip



STAR HFT

PXL sensor threshold operation point

- The noise level was set at ~2 x 10^{-6} for the cosmic ray run. At this noise rate, the measured operating point (taken from beam tests) is shown above.



Threshold = $\mathrm{Th}_{1.5*10E\text{-}6\ fake\ hit\ rate}$ – Offset $_{from\ labThScan}$

σ_{noise} = 1.33 mV

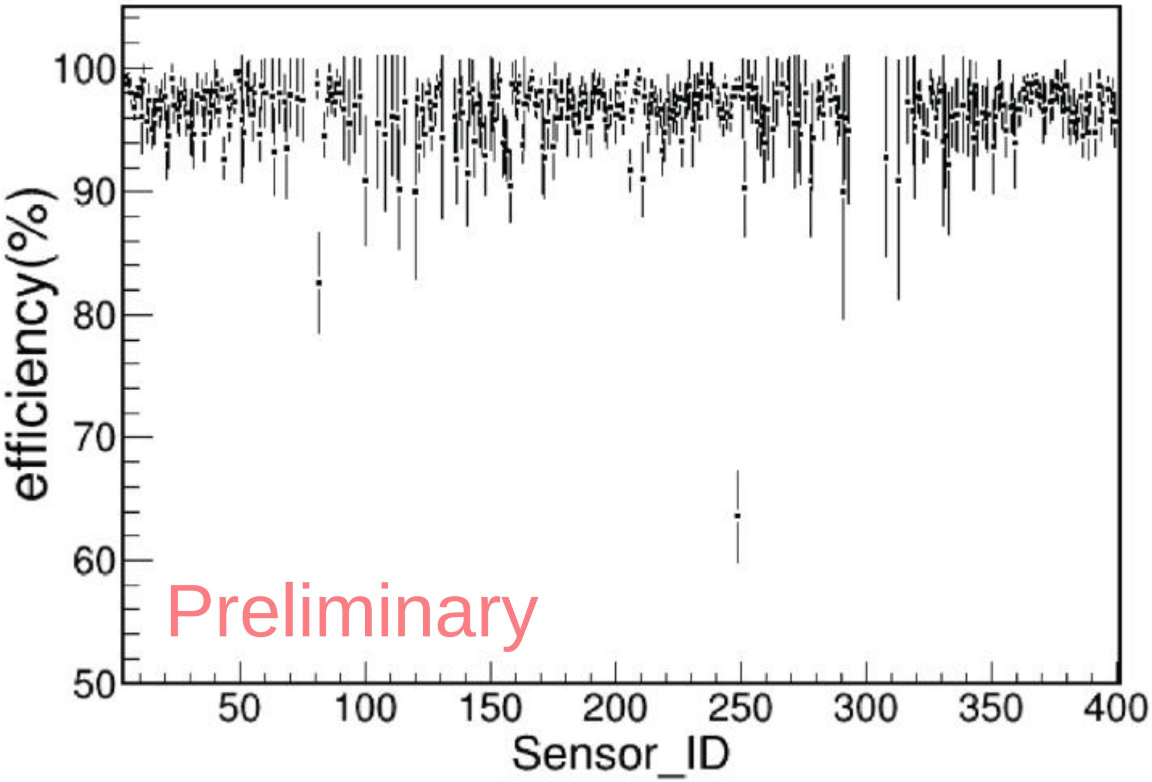
Threshold = 5.48 mV = 4.12 σ_{noise}

STAR HFT

PXL hit efficiency

preliminary results based on the cosmic ray data

Note: this data was taken before the final detector optimizations



PXL sensor efficiency measured with cosmic ray

Average = 97.2 %