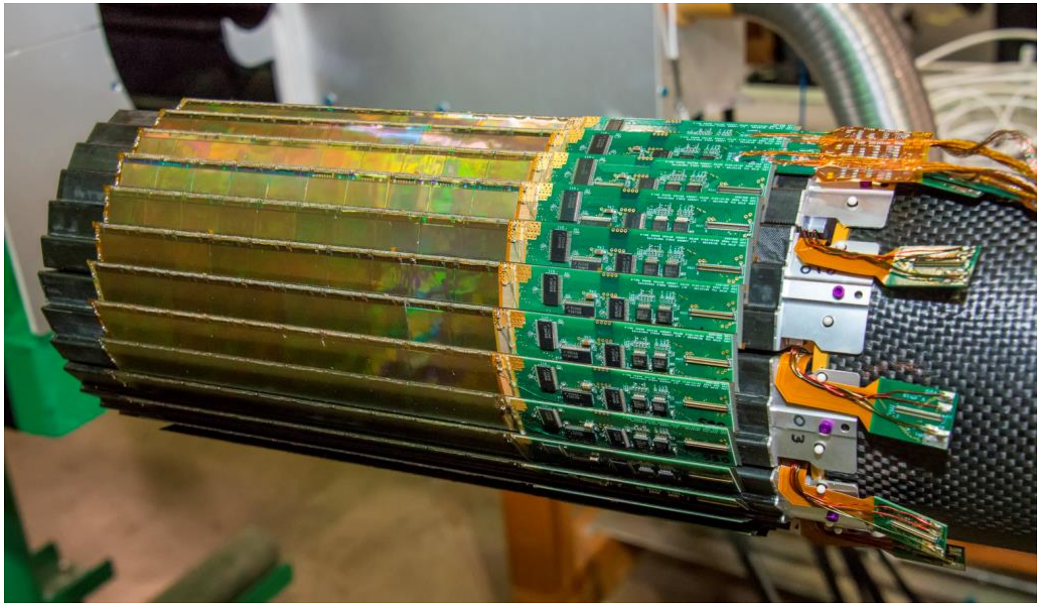
The STAR PXL detector cooling system



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UT at Austin: Jo Schambach

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

Lawrence Berkeley National Laboratory

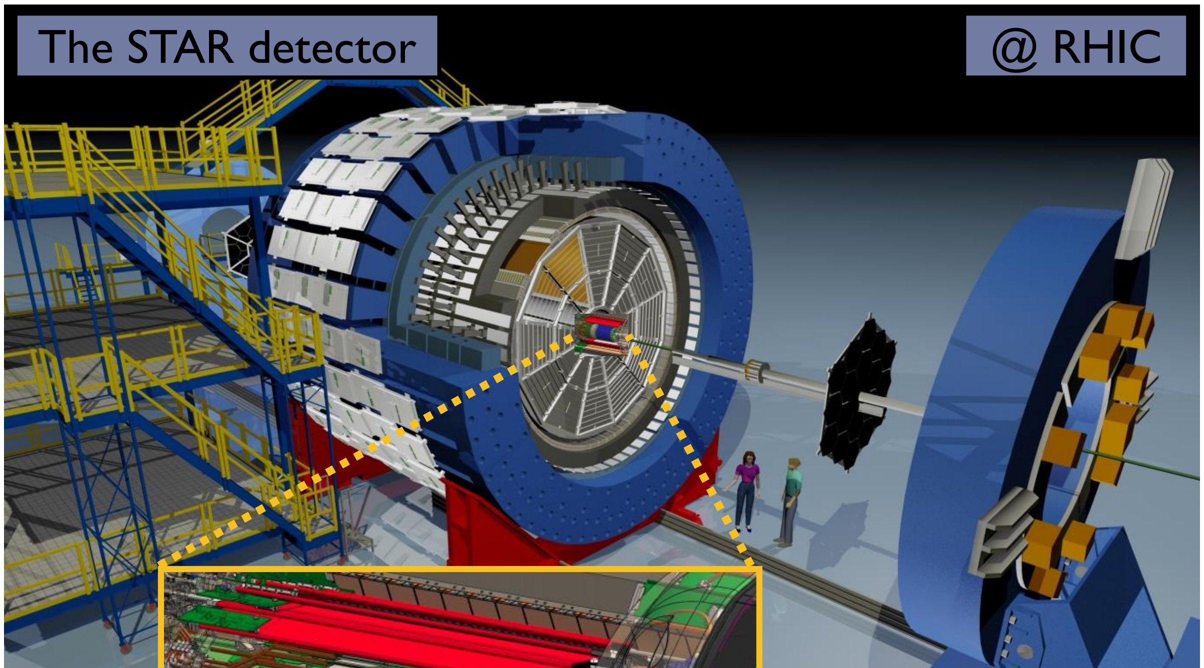
Outline

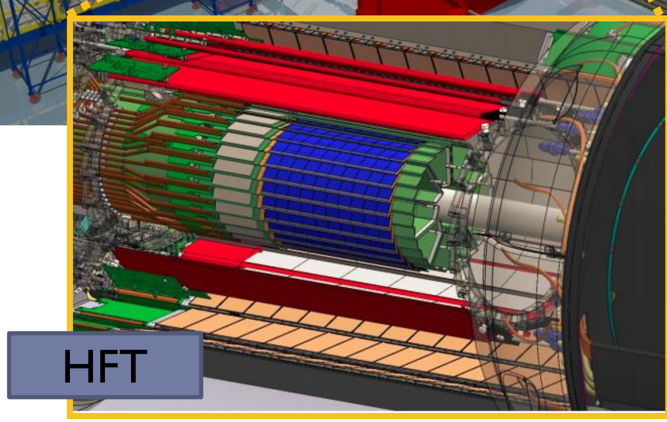
- The MAPS-based PXL detector for STAR
- PXL cooling system
- HFT status and performance
- Conclusions

STAR HFT Physics Motivation

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

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



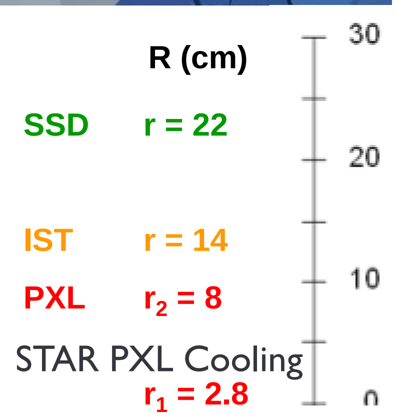


Need to resolve displaced vertices in high multiplicity environment

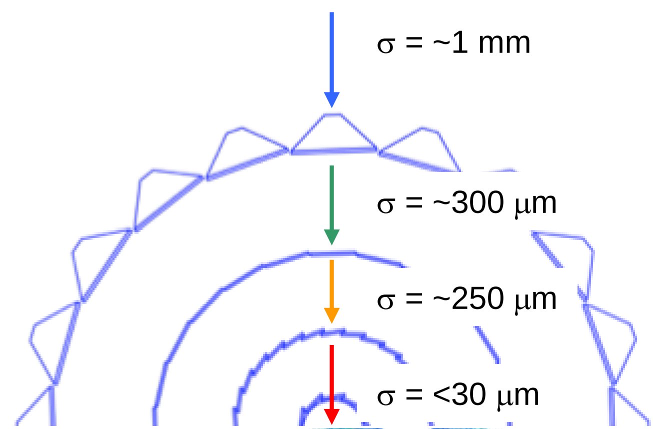
TPC – Time Projection Chamber (main tracking detector in STAR)

HFT – Heavy Flavor Tracker

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



Tracking inwards with gradually improved resolution:



HFT Subsystems: PiXeL detector (PXL)

First vertex detector at a collider experiment based on ***Monolithic Active Pixel Sensor*** technology

PXL Detector Design Parameters

DCA Pointing resolution	(10 ⊕ 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	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 $2*10^{11}$ to 10^{12} 1MeV n eq/cm^2
Rapid detector replacement	< 1 day

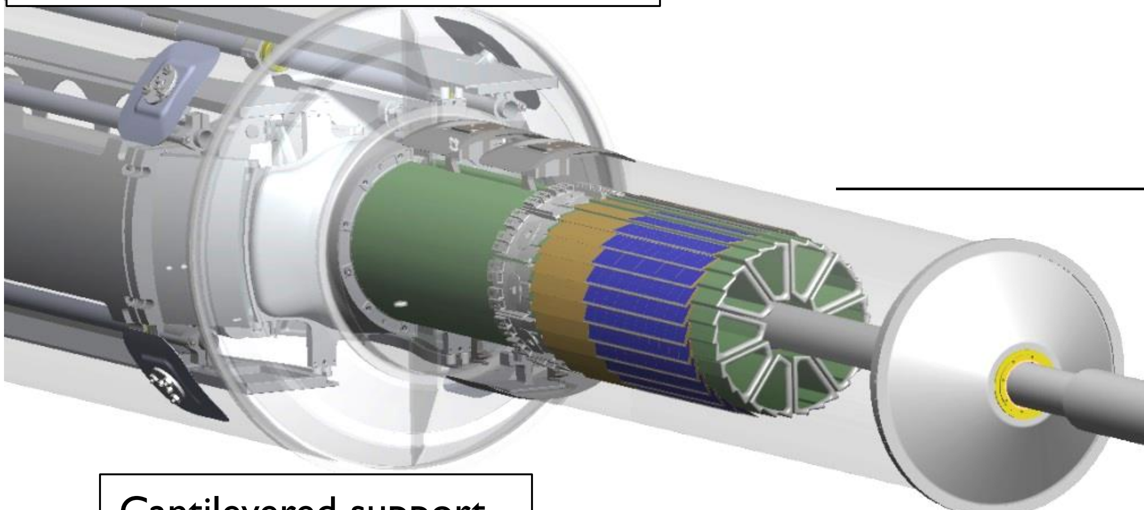
356 M pixels on ~0.16 m^2 of Silicon

PXL System Overview

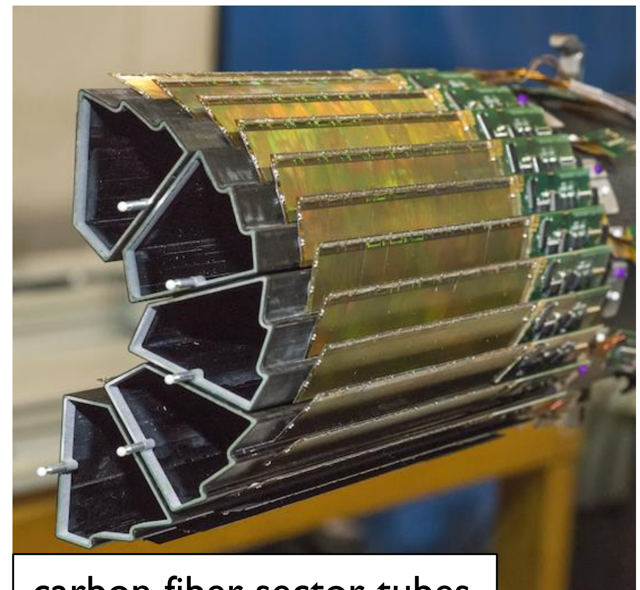
10 sectors total
5 sectors / half
4 ladders / sector
10 sensors / ladder

Highly parallel system

Mechanical support with kinematic mounts (insertion side)



Cantilevered support

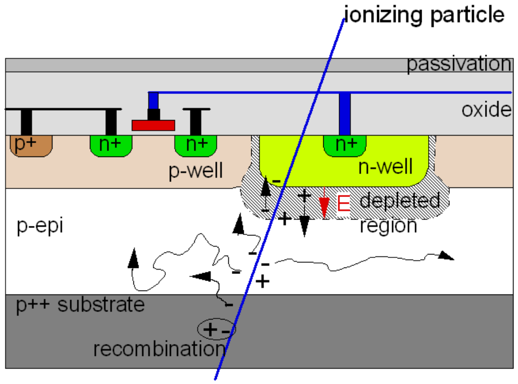


carbon fiber sector tubes (~ 200 µm thick)

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

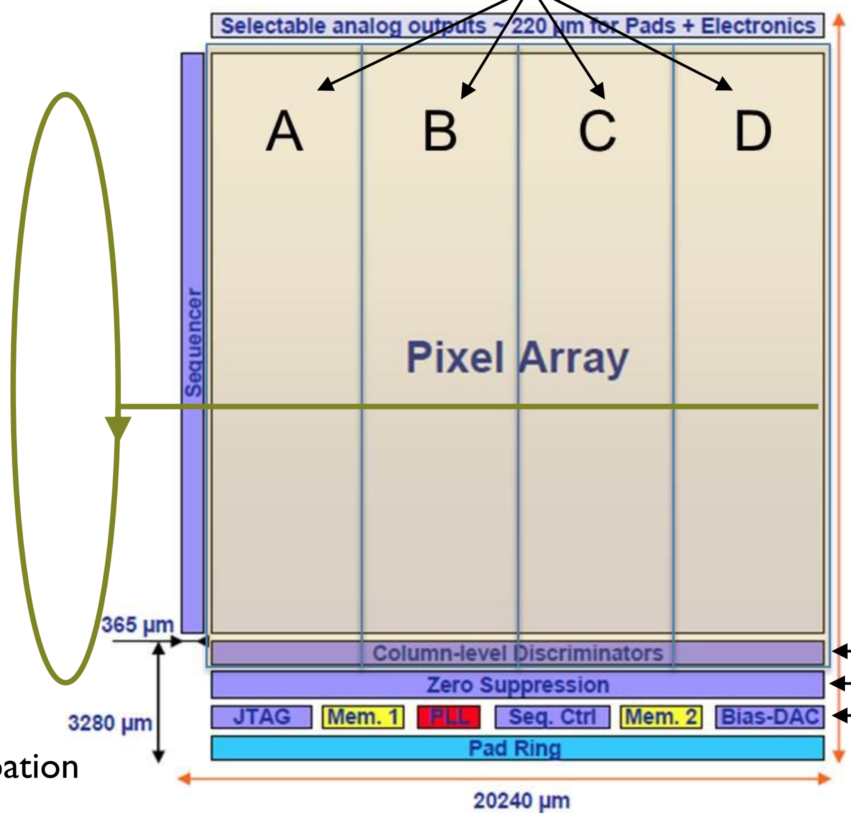
PXL sensor

- *Ultimate-2:* third generation sensor developed for PXL by the PICSEL group of IPHC, Strasbourg
- *Monolithic Active Pixel Sensor* technology



4 sub-arrays to help with process variation

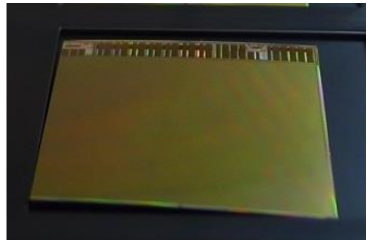
- High resistivity p-epi layer
  - Reduced charge collection time
  - Improved radiation hardness
- S/N ~ 30
- MIP Signal ~ 1000 e-
- **Rolling-shutter readout**
  - A row is selected
  - For each column, a pixel is connected to discriminator
  - Discriminator detects possible hit
  - Move to next row
- 185.6 µs integration time
- ~170 mW/cm² power dissipation



- **Pixel matrix**
  - 928 rows * 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 Material Budget

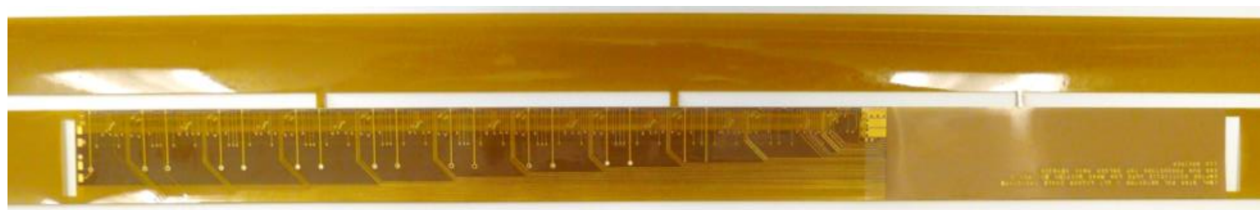
- Thinned Sensor
  - 50 μm
  - 0.068% X_0



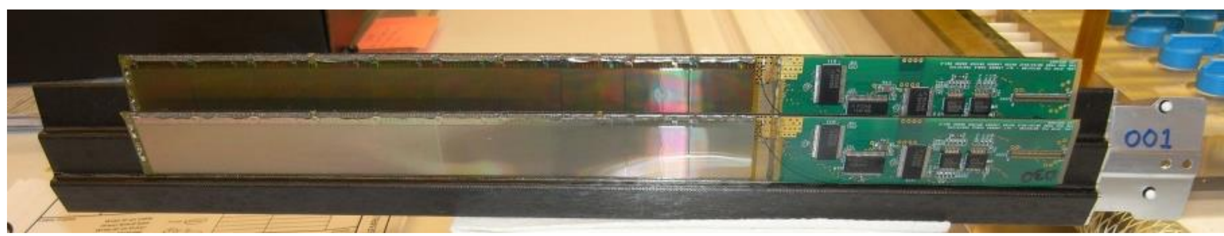
- Curved sensor
- 40-60% yield after thinning, dicing and probe testing
- Fully characterized before installation

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

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



- 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**

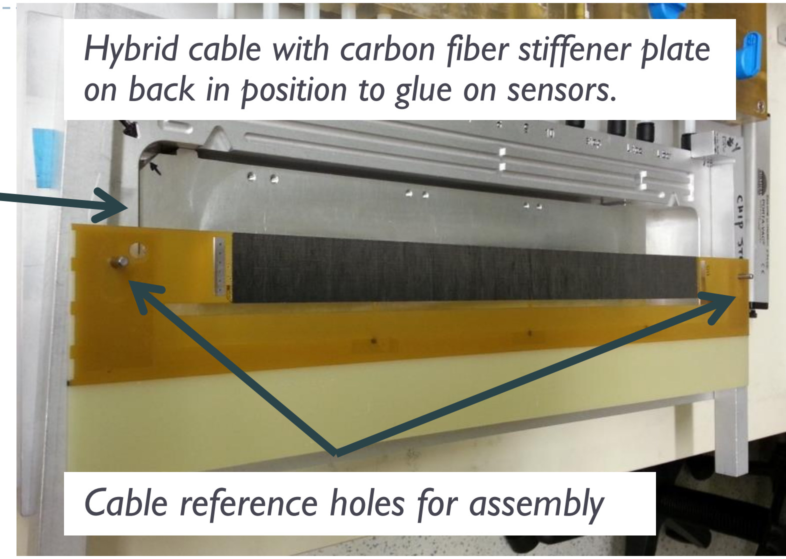
(0.492% X_0 for the Cu conductor version)

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

PXL Assembly and Installation

Sensor positioning

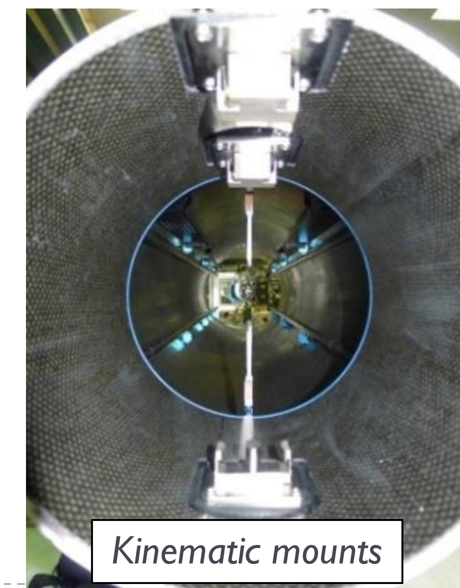
- Precision vacuum chuck fixtures to position sensors by hand
- Sensors are positioned with butted edges. Acrylic adhesive prevents CTE difference based damage


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

Cable reference holes for assembly

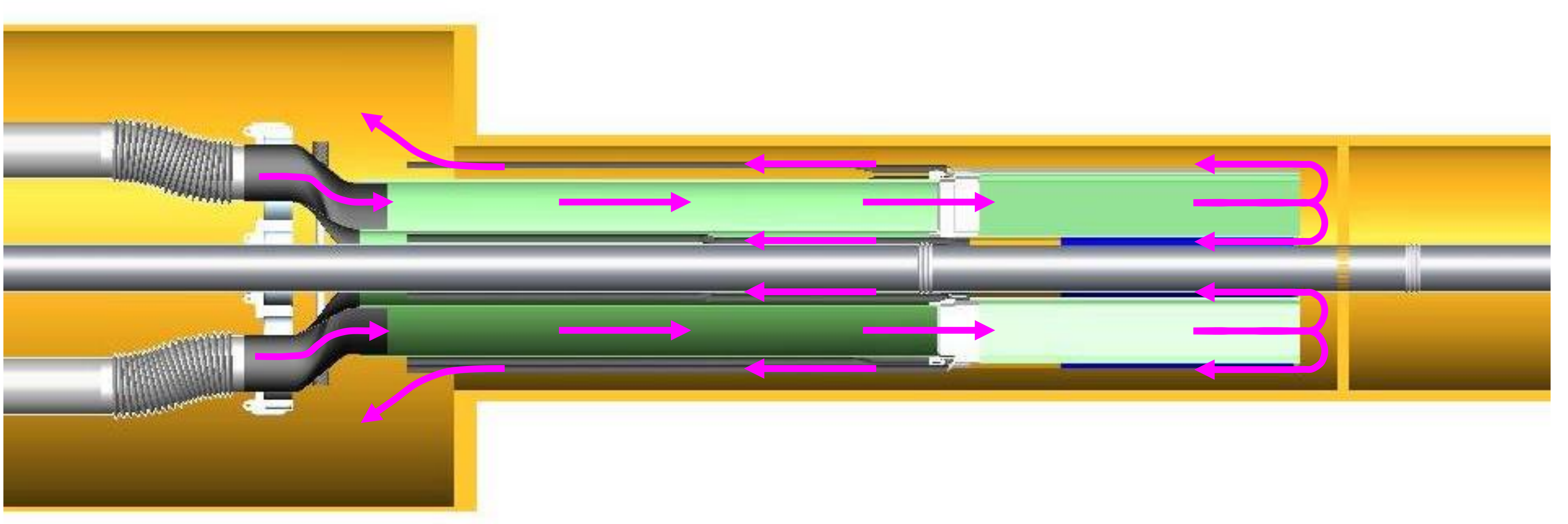
Novel insertion approach

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


Kinematic mounts

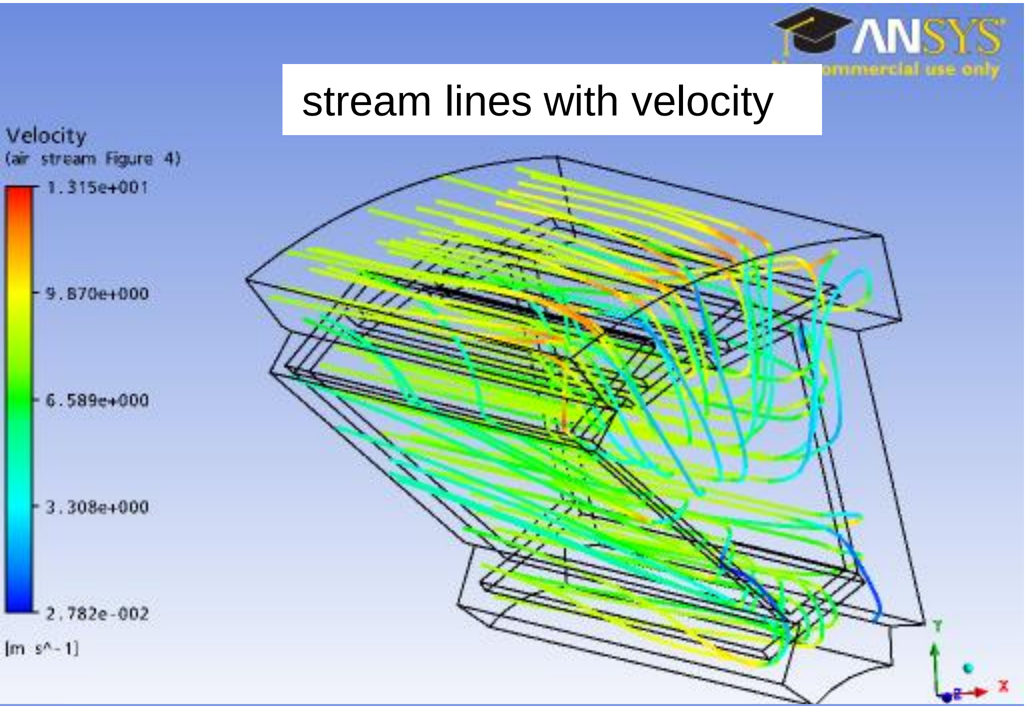
Air cooling of silicon detectors - CFD analysis

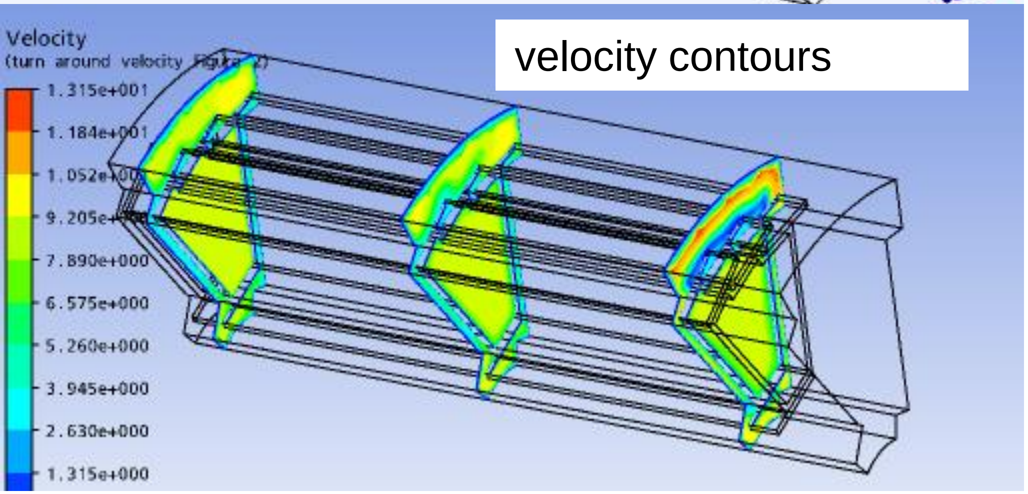
- Silicon power: 100 raised to 170 mW/cm^2
  (~ power of sunlight)
- 350 W total Si + drivers



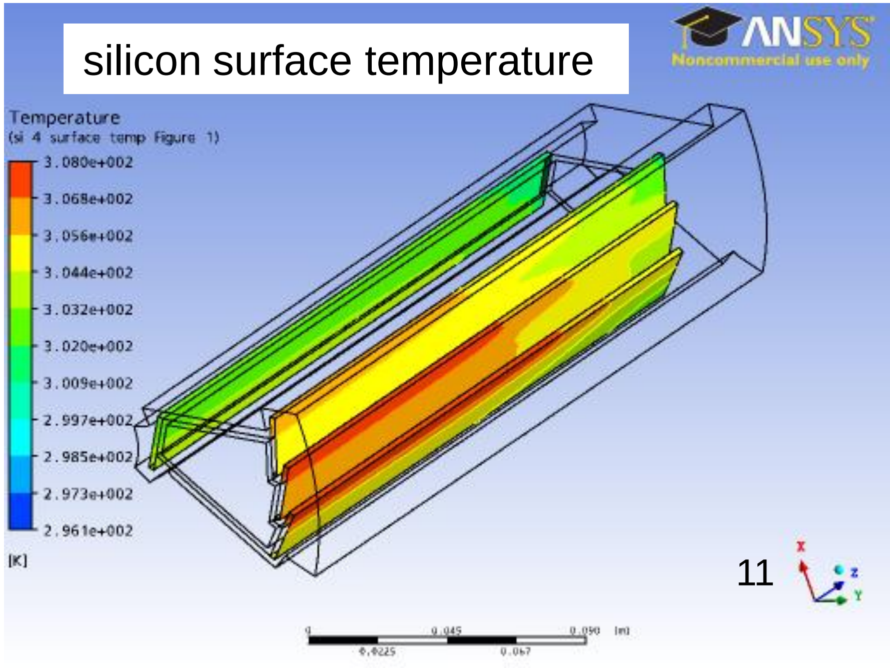
air flow path – flows along both inside and outside surface of the sector

Air cooling – CFD analysis

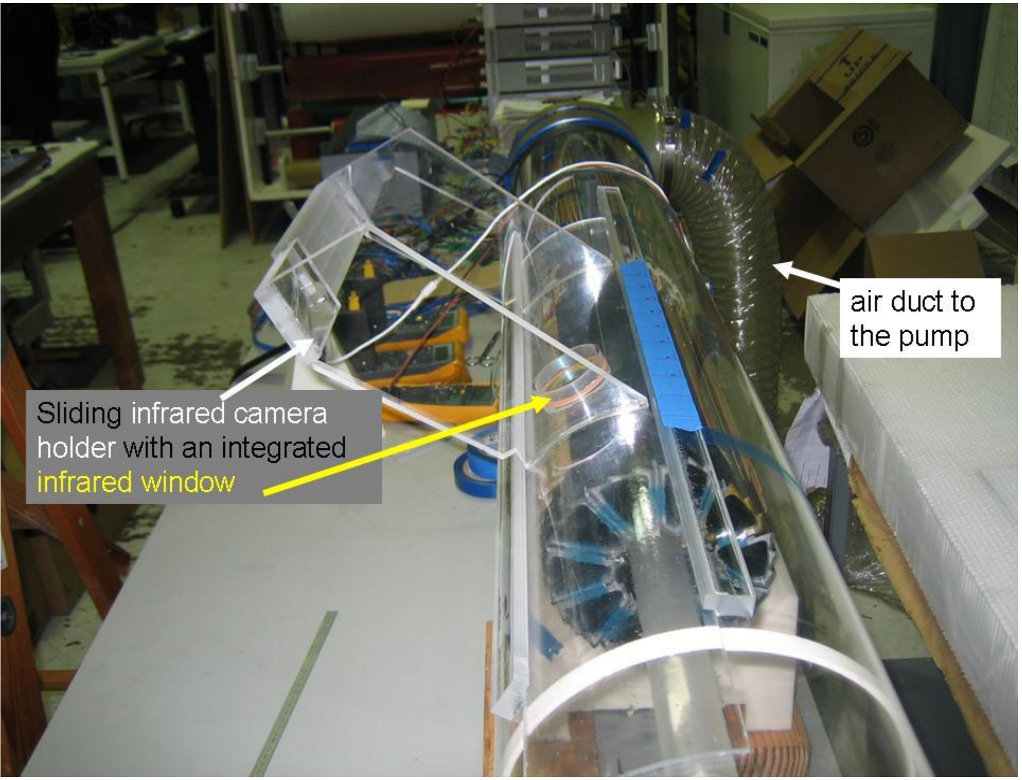




- air flow velocity 9-10 m/s
- maximum temperature rise above ambient: 12 deg C
- sector beam surface – important component to cooling
- dynamic pressure force 1.7 times gravity

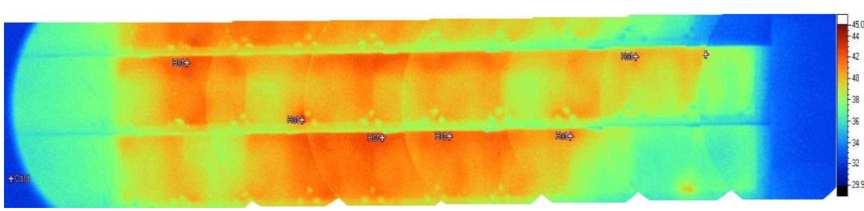


Full scale mockup to verify cooling capability



- Platinum on thinned silicon to simulate detector chip heat load
- Additional heaters to reproduce driver heat sources
- Input and output thermocouple monitoring of air temperature
- Thermistors distributed on mockup pixel ladders
- IR camera to measure surface temperatures
- Air blower with static head of 9 inches of water
- air velocities measured with a hot wire velocity sensor

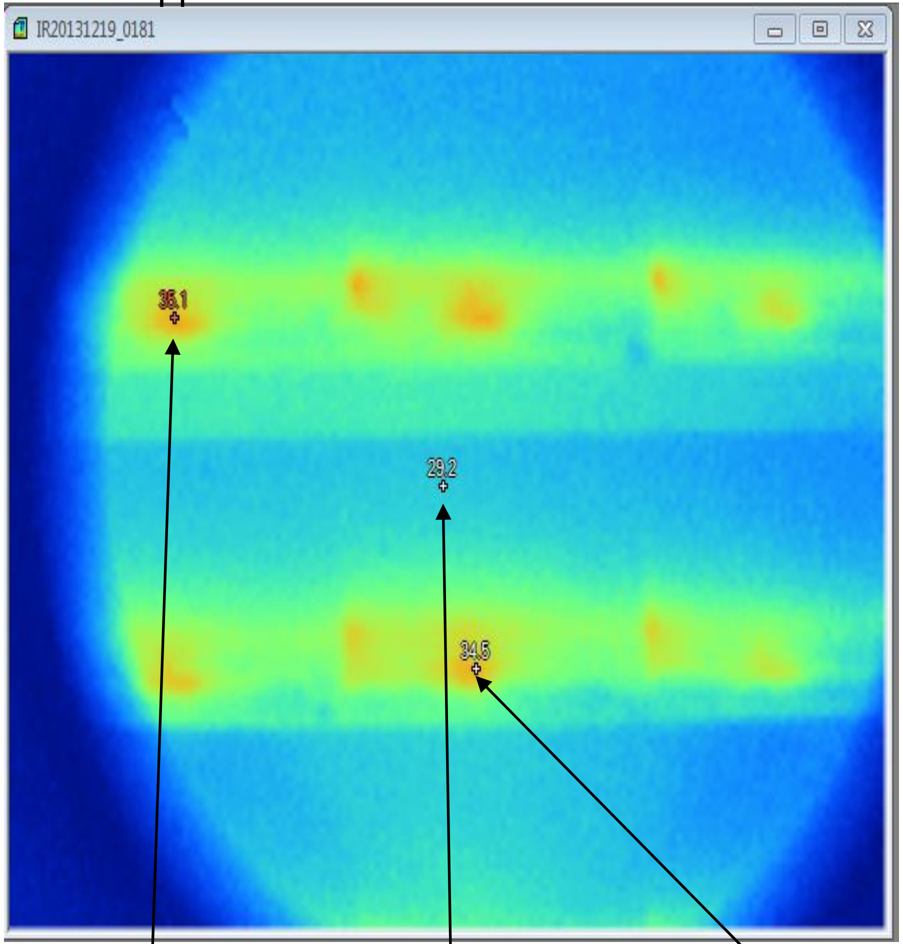
In these tests we failed to get good total mass flow measurements which complicated specifying the final cooling blower system.



Thermal image of sector-1 at 290 W dissipated in the detector and at the air flow speed of 12.2 m/s. The image was stitched from 8 individual images of small subsections. Ambient air temperature 31 °C

Result: ΔT = 11 °C with 10.4 m/s air velocity, verifying CFD estimate test of operating PXL system with full power and cooling flow

Ladders viewed through IR window installed in the Pixel Support Tube



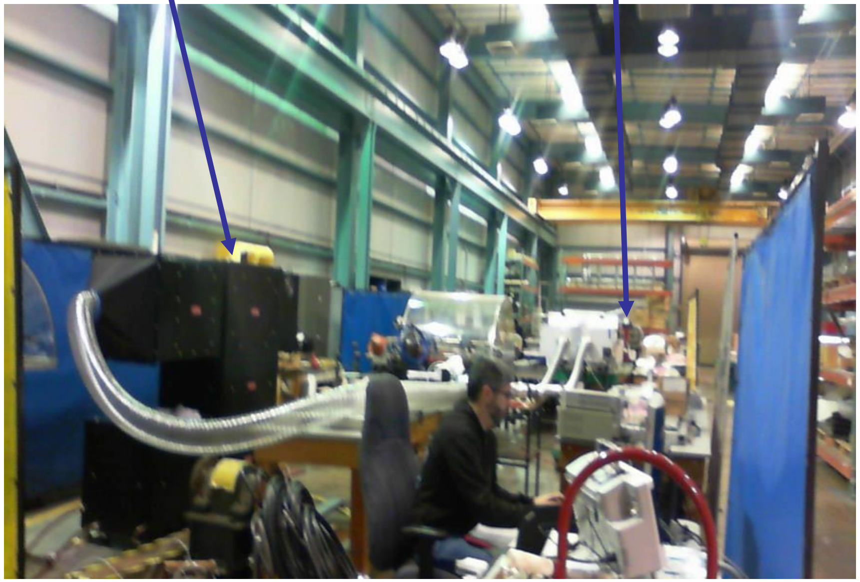
hottest point on the chip, middle of the digital section.

center of the middle chip (active region)

center of the digital section of the middle chip

Air Innovations Cooling air supply .14 m^3/s at 2200 Pascal temperature regulated to 23±1 °C

PXL detector assembly



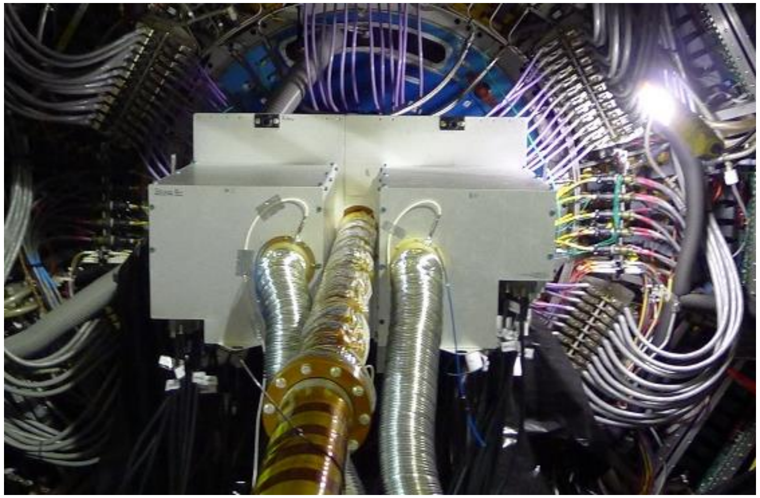
12 °C MAX deviation from ambient

Cooling unit and Safety

Interlocks (immediate power shut down)

- ECU – Cooling Unit
  - Low Air Flow
  - Low/High Air Temperature
- STAR interlock
  - Any condition potentially harmful for STAR

ECU Cooling Unit

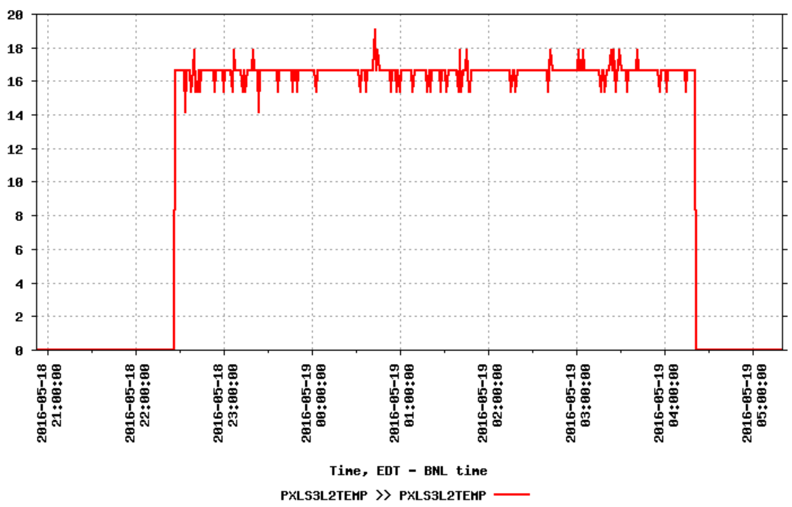


Air Flow sensors at detector inlet

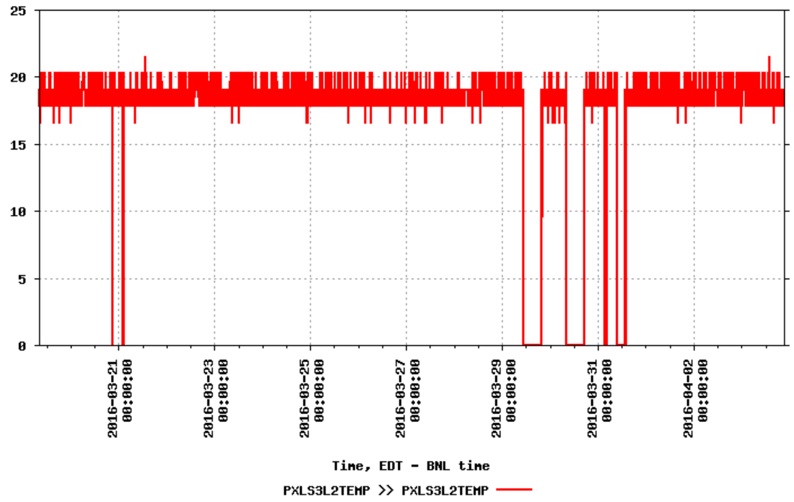
Running PXL temperature monitoring

Typical ladder temperature trend from online monitoring

- Temperature diode reading from the last ladder sensor
- Relative measurement
- Plots:
  - Sector 3 Ladder 2
  - Not calibrated



~ 6h RHIC fill

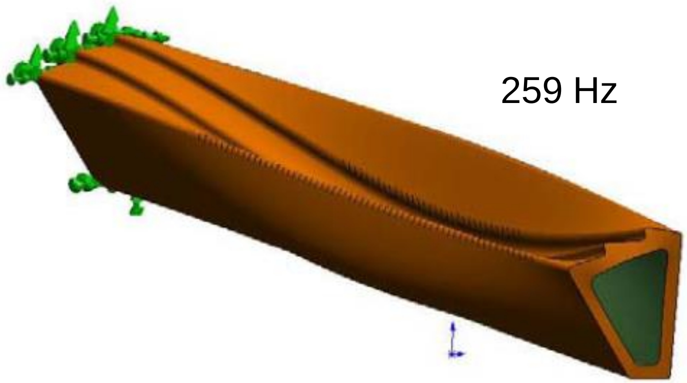


~ 2w cosmic run

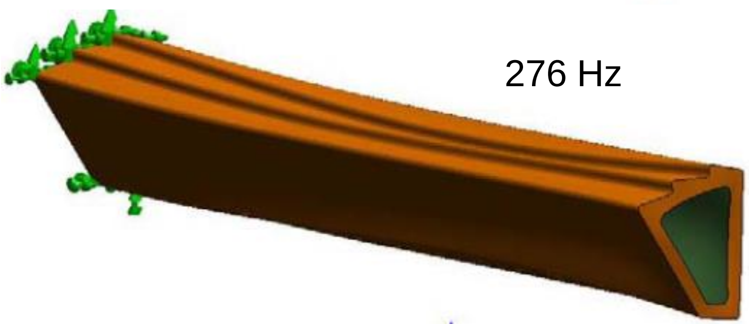
Static displacement and vibration induced by cooling air flow

- Sector vibration modes were examined with FEA
- Prototype sector vibrations measured with airflow tests. This was determined to be less time consuming than setting up transient CFD calculations.
- Measurement of completed detector

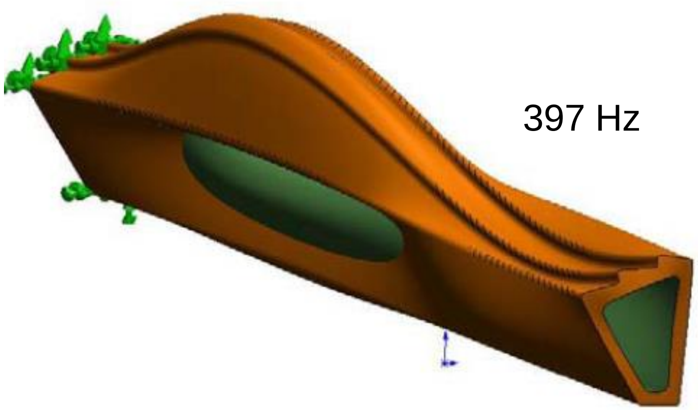
vibration modes with reinforced end cap



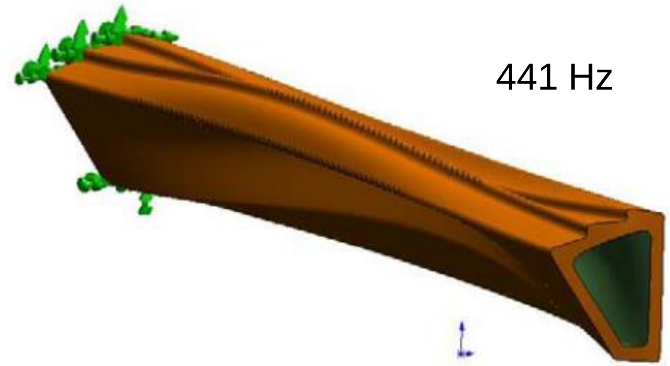
259 Hz



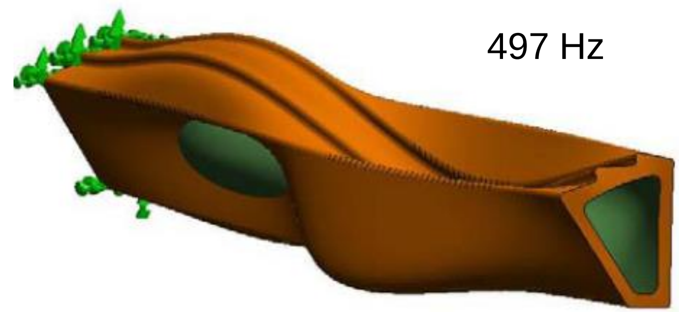
276 Hz



397 Hz



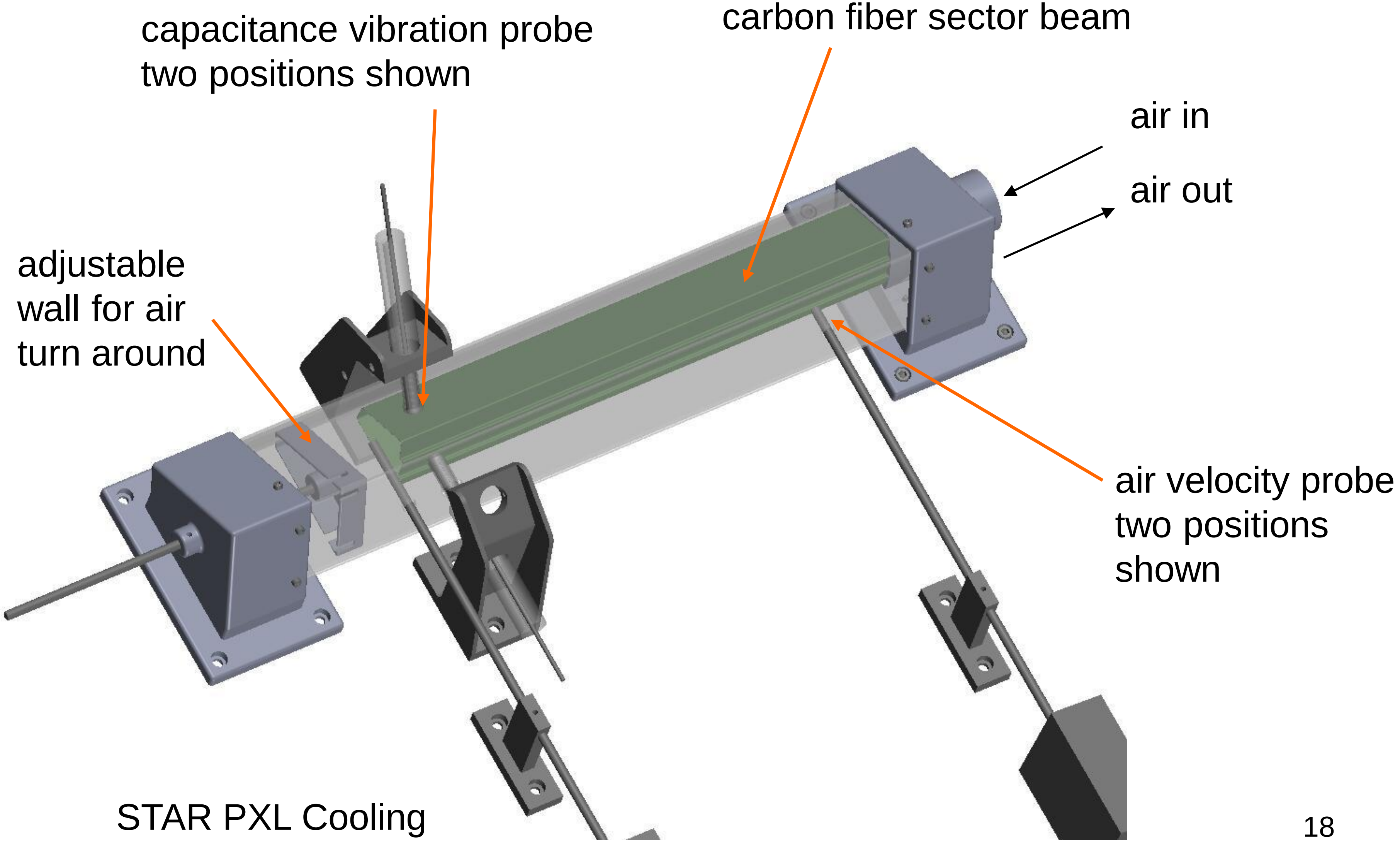
441 Hz



497 Hz

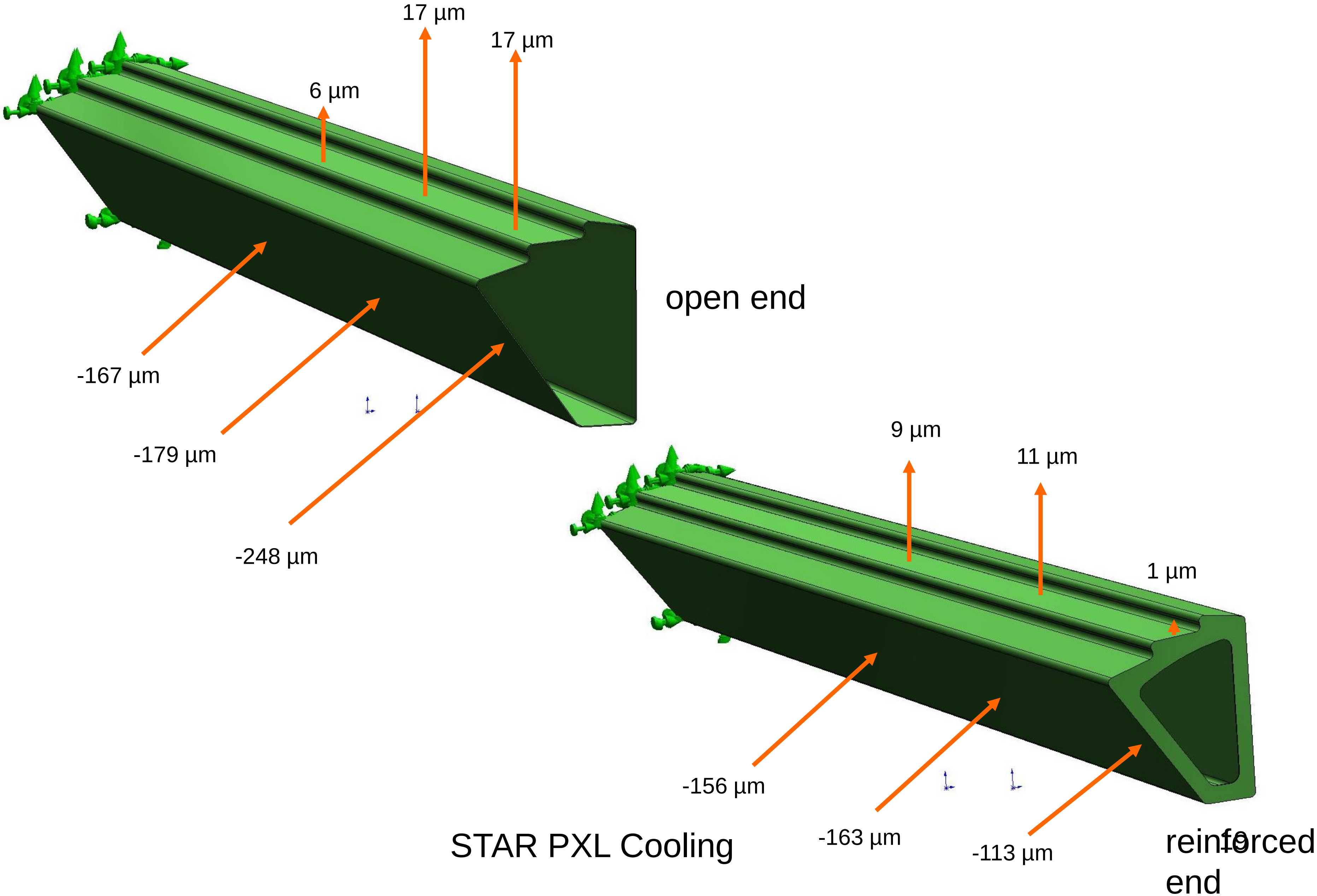
- The message
  - Lots of complicated modes close in frequency
  - End cap raises frequencies a bit

wind tunnel setup to test vibration and displacement

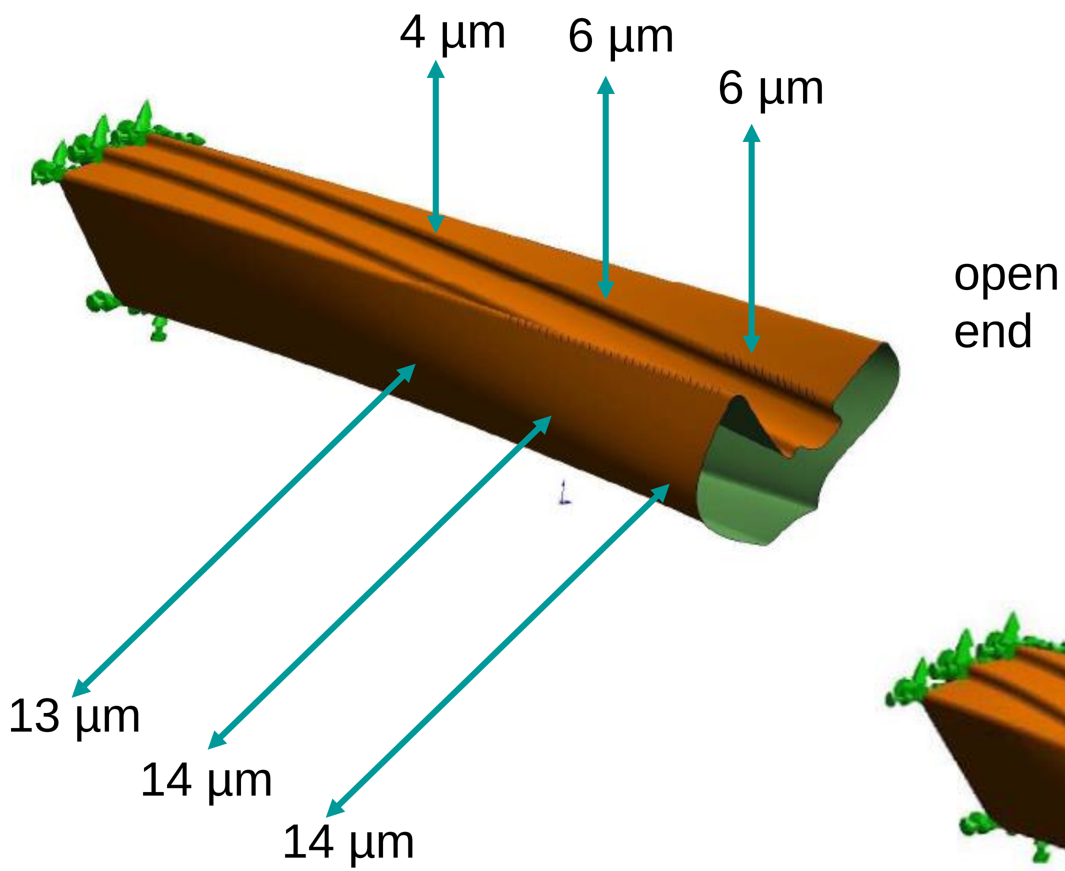


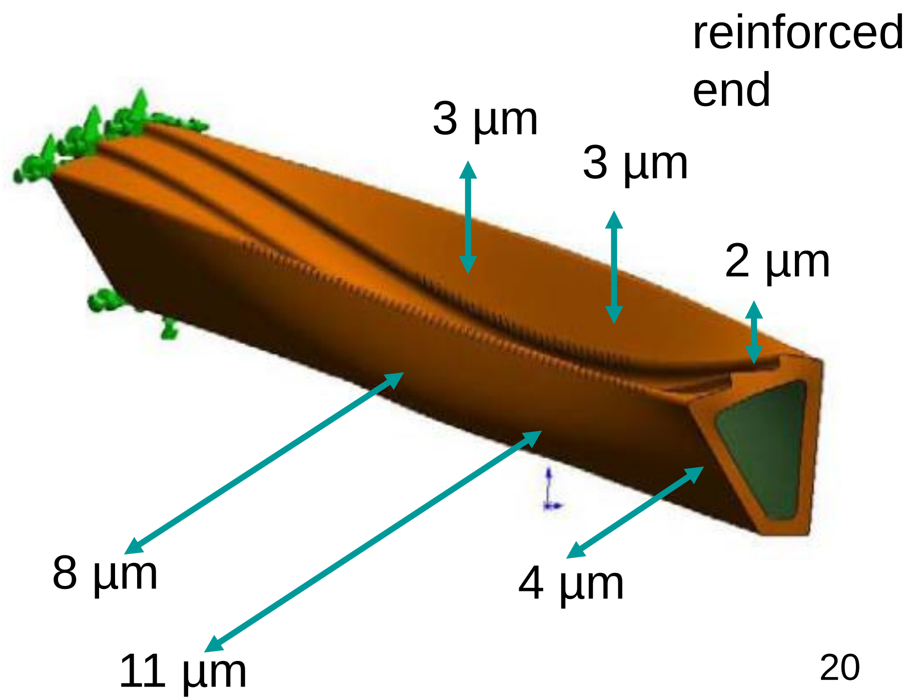
C:\Documents and Settings\Howard Wieman\My Documents\aps project\mechanical\PXL phase 1 sept 2008\sector ph1 wind tunnel.SLDASM

measured static deformation from 9 m/s air flow

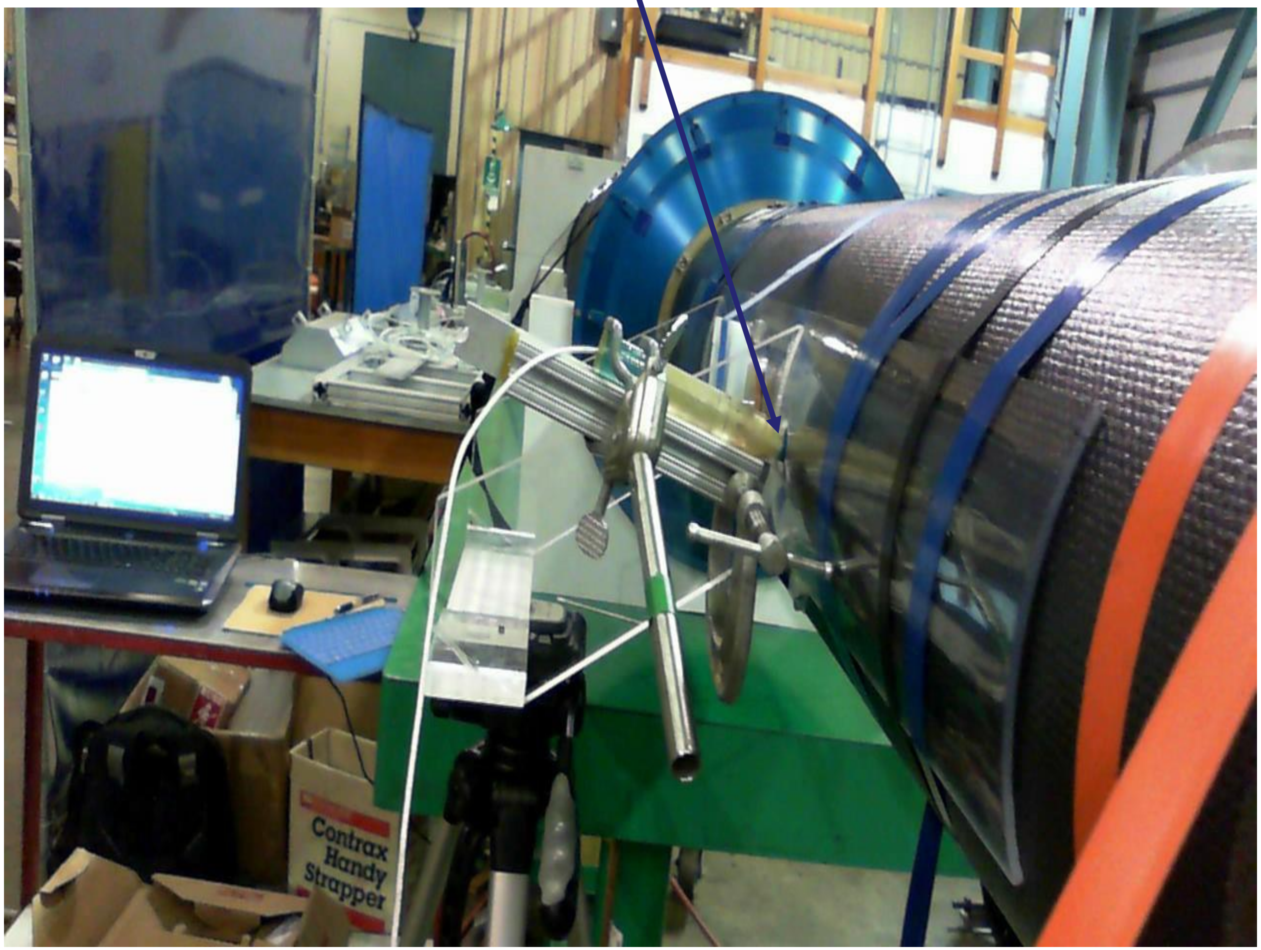


measured vibration (RMS) induced by 9 m/s air flow





Radial sector motion measured with capacitive probe inserted through hole in PST

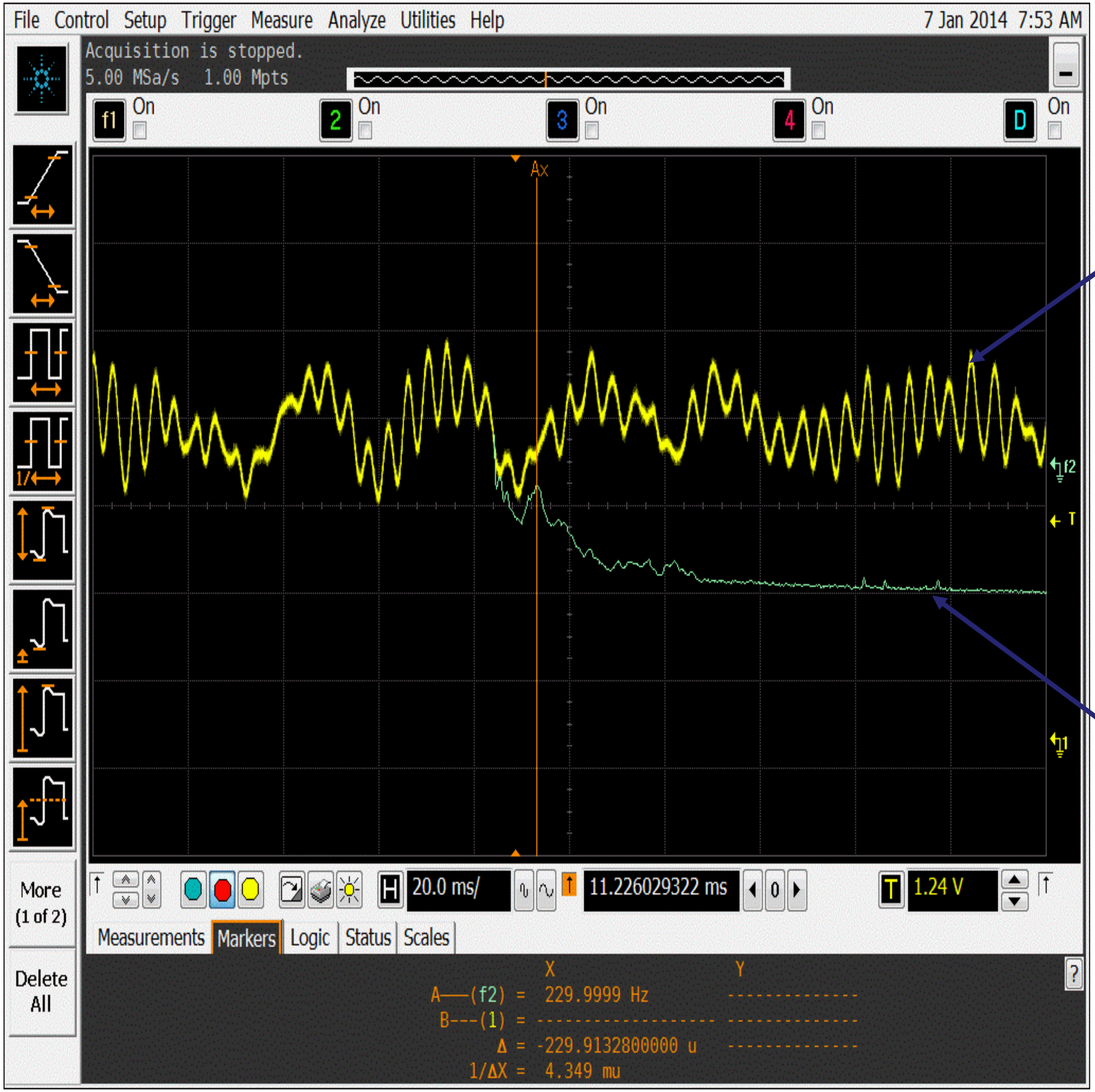


capacitive probe measurement of completed PXL detector

North half sectors populated with operating ladders. South half populated with empty sector tubes. System operated with full cooling air

Typical screen shot at full air flow

capacitive probe measurement of completed PXL detector



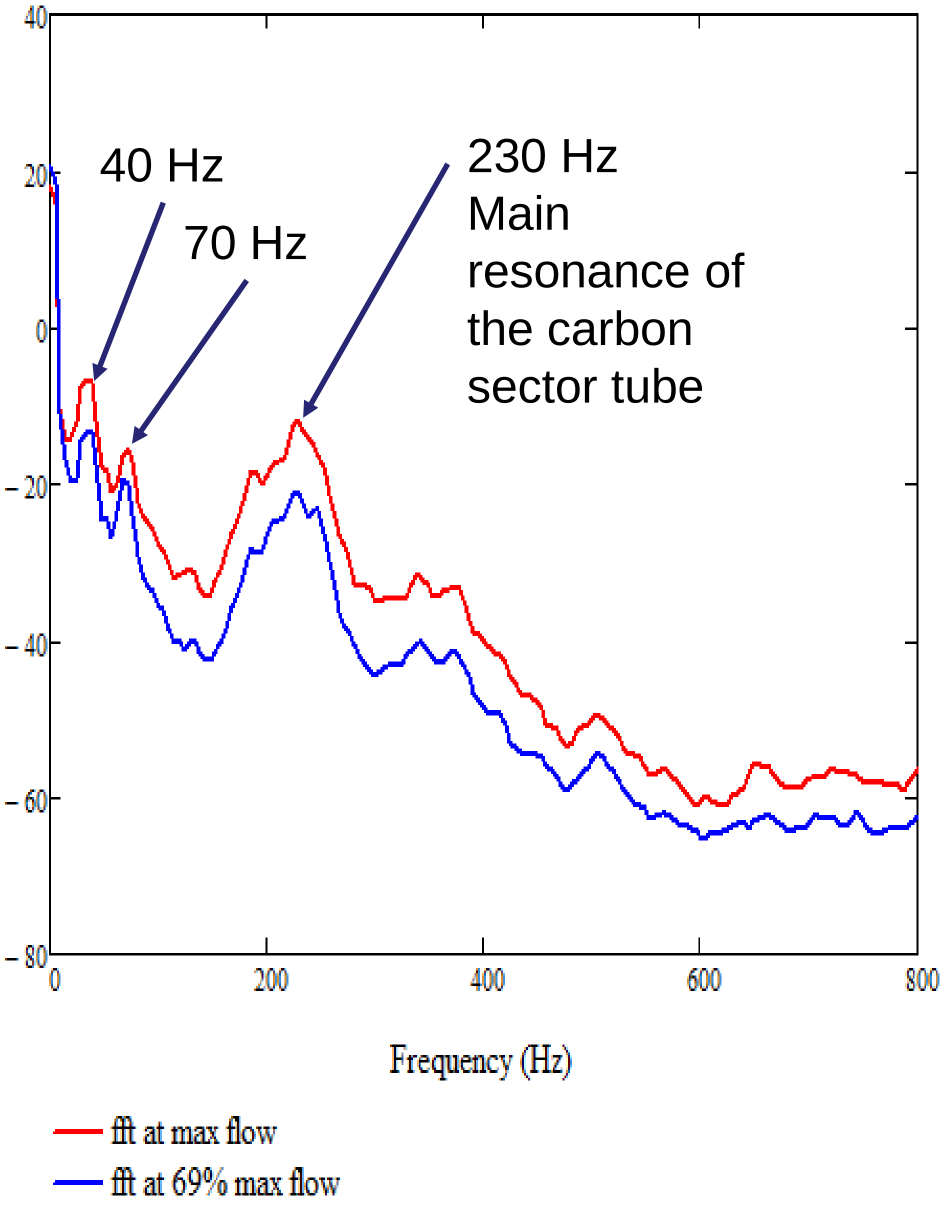
Probe signal

Stdev = 5 μm

Probe conversion = 1 μ

FFT, see next page for more detail

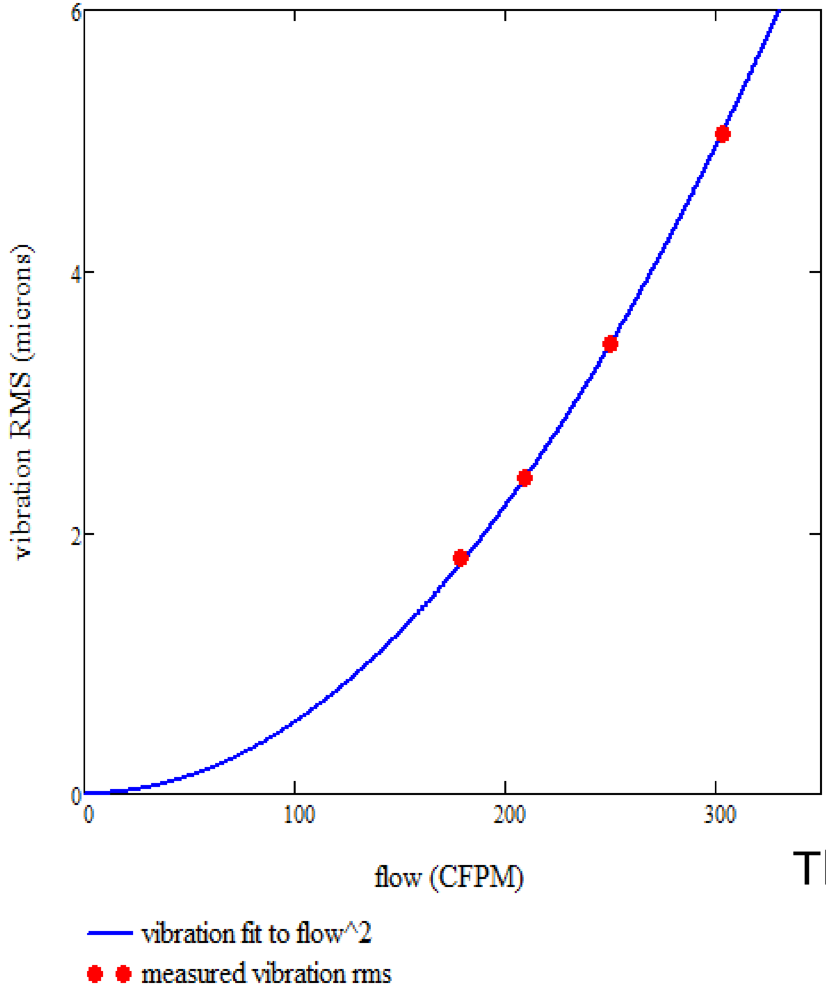
Fourier transform of sector vibration



capacitive probe measurement of completed PXL detector

close to 260 Hz from original FEA simulation

Measured sector radial vibration as a function cooling air flow for edge ladder



capacitive probe measurement of completed PXL detector

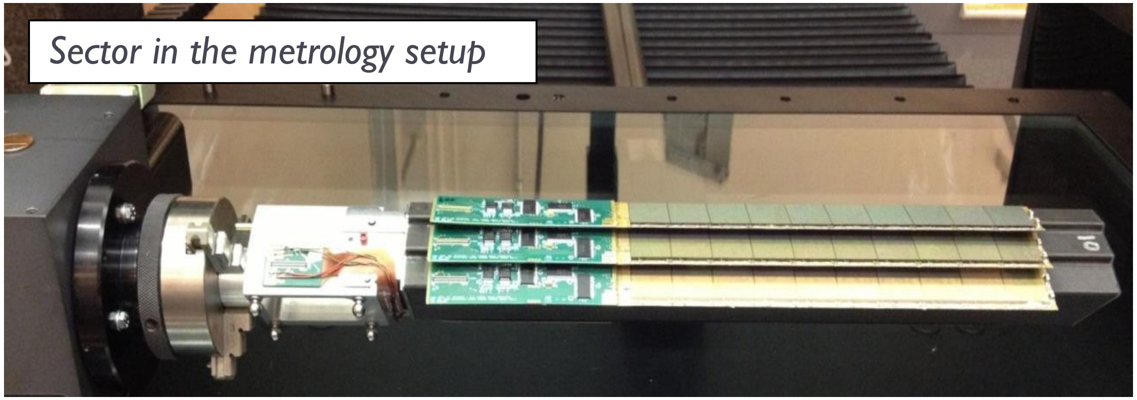
The measured vibration with no air flowing:
35 nm RMS

cooling air induced vibration and static displacement

capacitive probe measurement of completed PXL detector

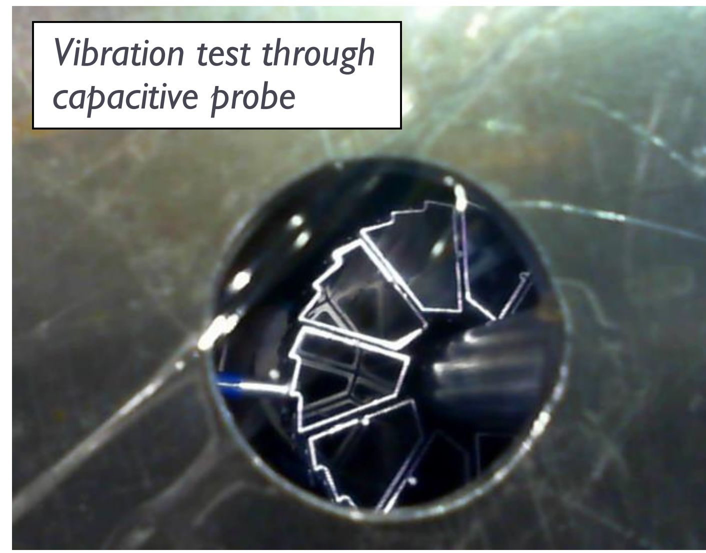
Sector vibration in the radial direction scales as:	$flow^2$
Sector vibration at full flow:	5 µm RMS
Sector DC displacement scales as:	$flow^2$
Sector moves in radially (static) at full flow:	25 µm - 30 µm

PXL Position Control



- 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

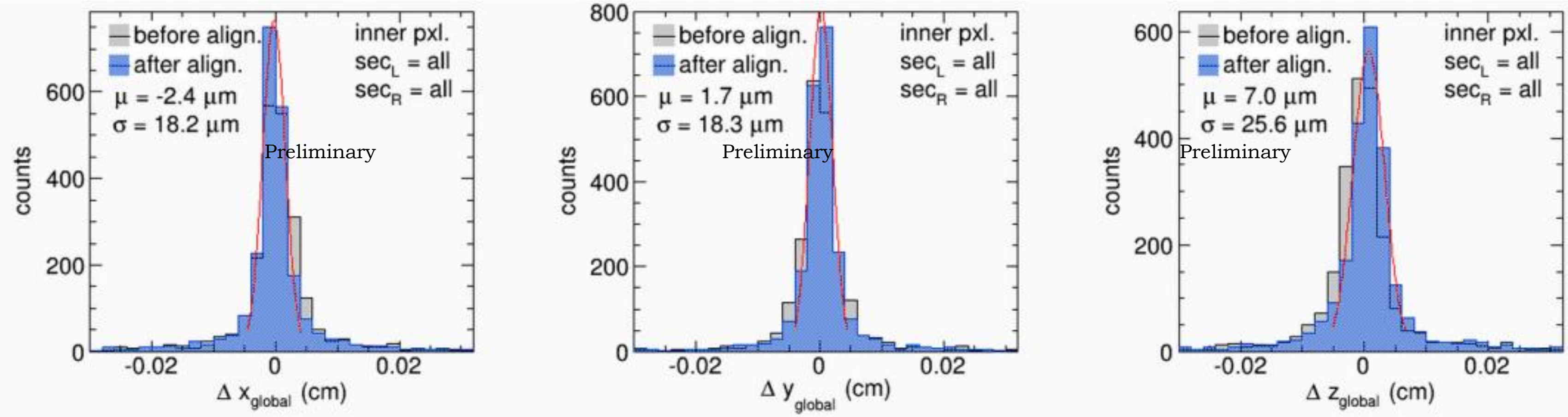


- Position stability
  - Vibration at air cooling full flow: ~5 μm RMS
  - Stable displacement at full air flow: ~30 μm
  - Stable displacement at power on: ~5 μm

  → Global hit position resolution: ~ 6.2 μm

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

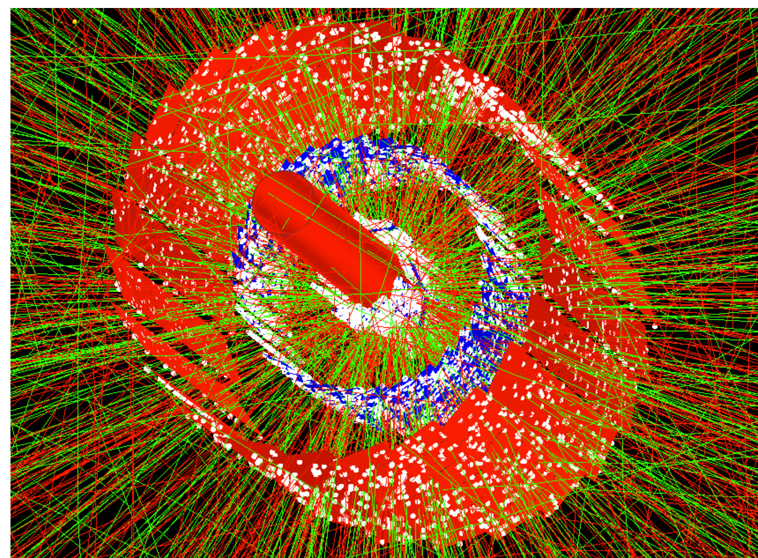
Performance: Hit Residuals and Track DCA



***Residuals** for detector-half pointing to the inner layer of the other half (from cosmic data)*

- PXL hit residuals (for cosmics) after sector alignment < 25 μm

200 GeV Au+Au event



Conclusions

- The STAR HFT has been successfully taking data in 2014, 2015 and 2016
- State-of-the-art MAPS technology proved to be suitable for vertex detector application
- The air cooling allowed for stable operations, with limited induced vibration and static displacement
- The HFT enabled STAR to perform a direct topological reconstruction of the charmed hadrons

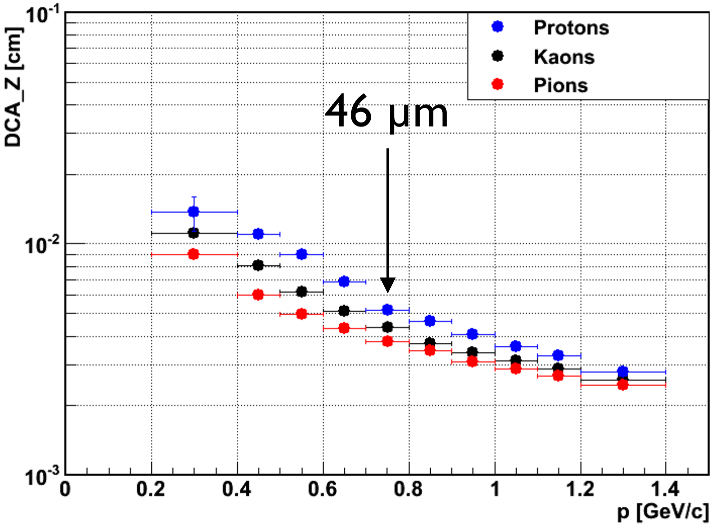
Thank you for your attention!

Thank you for your attention!

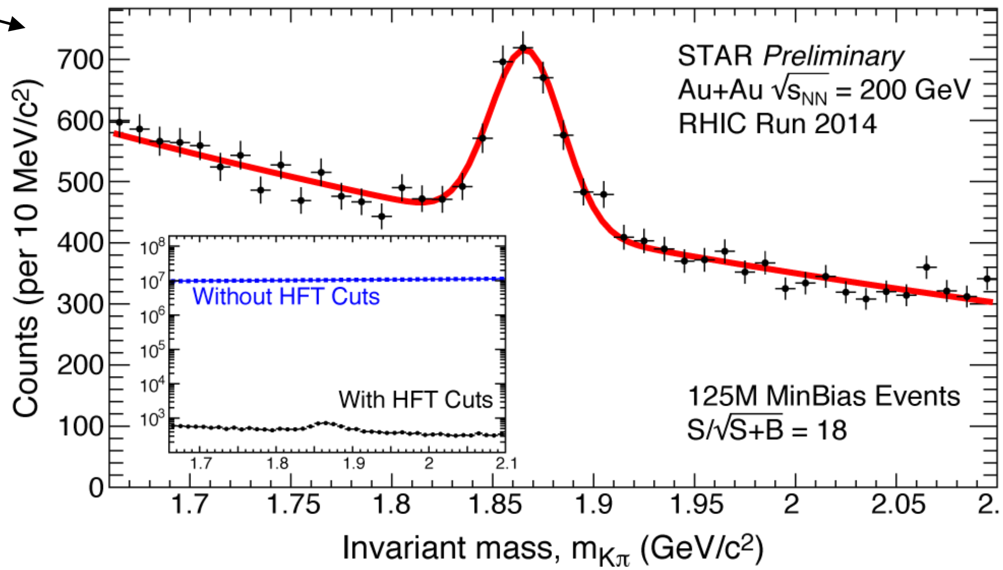
Backup slides

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



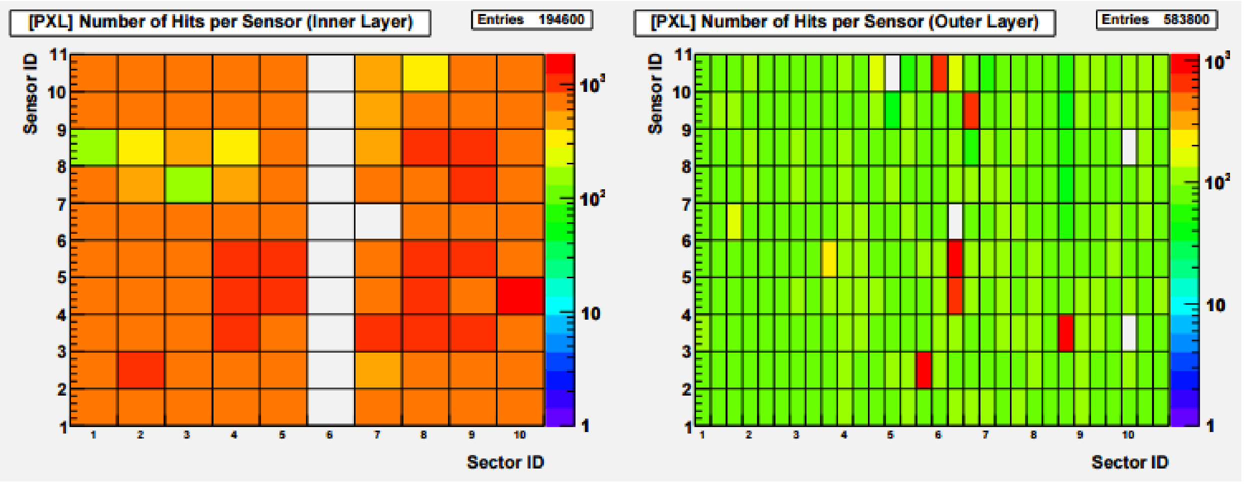
$D^0 \rightarrow K\ \pi$ production *in $\sqrt{s_{NN}}$ = 200GeV Au+Au collisions (partial event sample)*



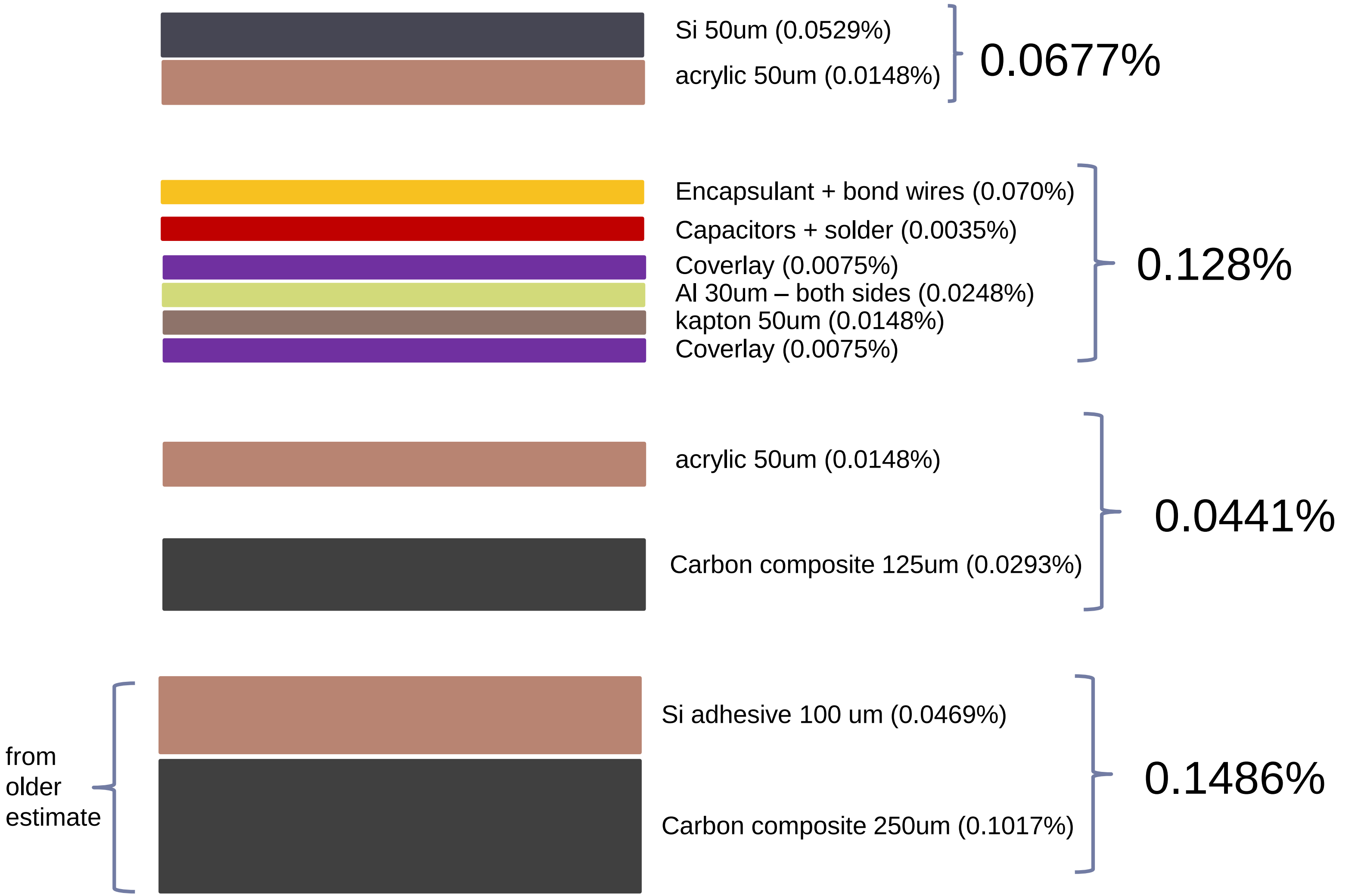
- Physics of D-meson productions
  - High significance signal
  - Nuclear modification factor R_{AA}
  - Collective flow v_2

HFT status and operations

- Collected minimum bias events in HFT 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: { ~ 1.5 Billion p+p, ~ 0.3 Billion d+Au } @ $\sqrt{s_{NN}}$ = 200GeV
- Typical trigger rate of ~0.8kHz with dead time <5%
- PXL status in 2016 Run
  - Latch-up induced damage:
    - 1 full ladder off
    - 5 sensors dead



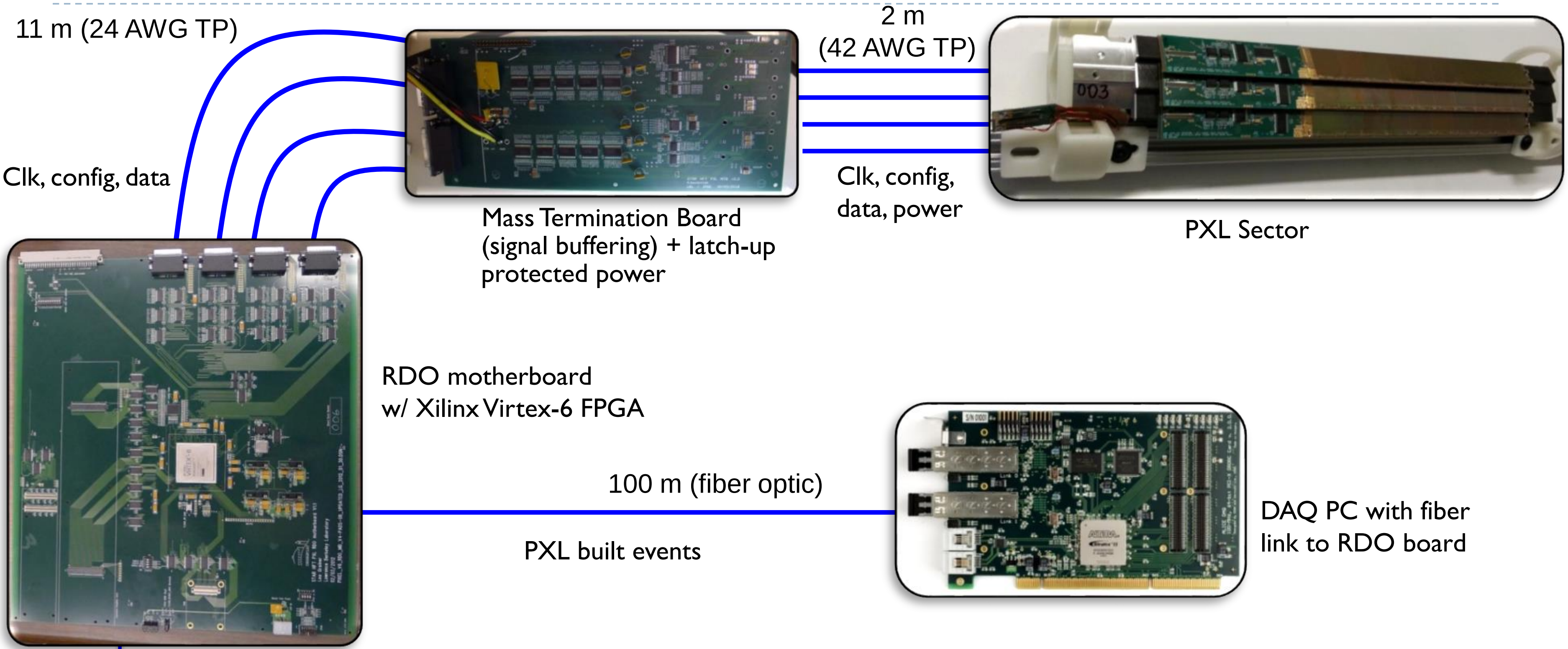
Radiation length in low mass area

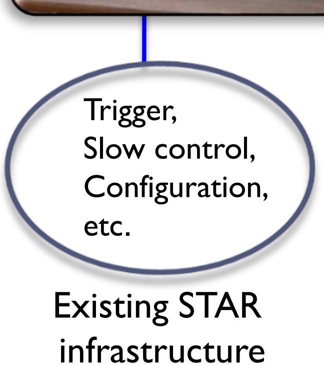


NOTE: Does not include sector tube side walls

Total = 0.388%

PXL Detector Powering and Readout Chain

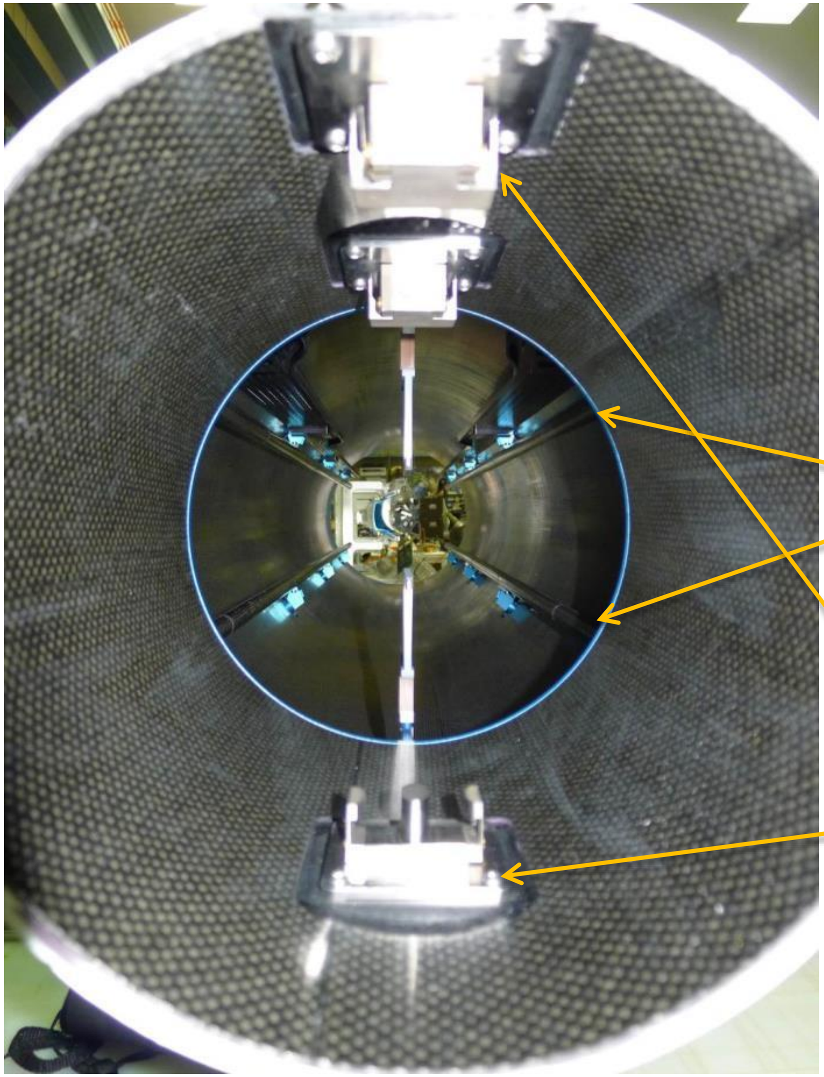




Highly parallel system

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

PXL insertion mechanics



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

Carbon fiber rails

Kinematic mounts