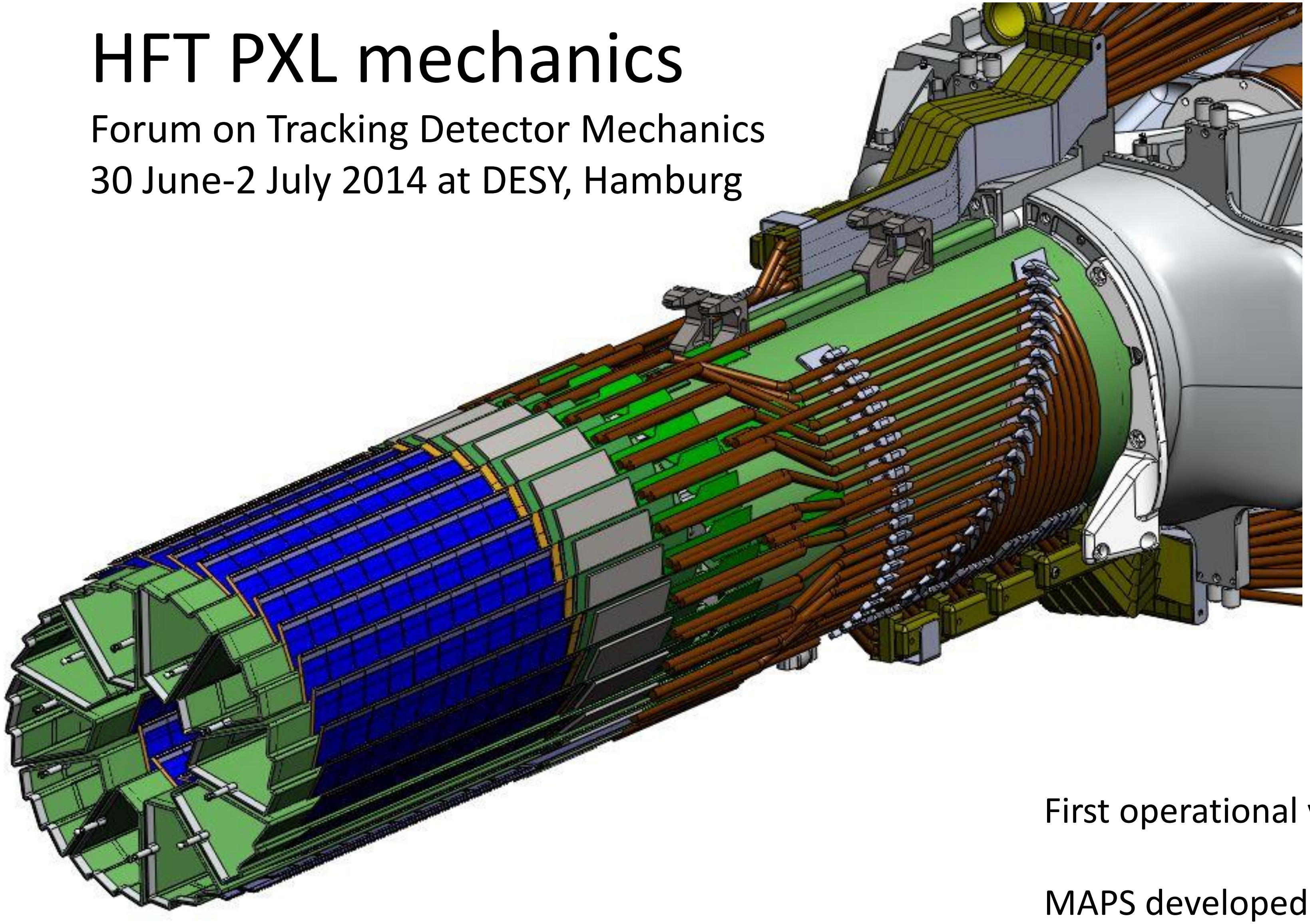
HFT PXL mechanics

Forum on Tracking Detector Mechanics
30 June-2 July 2014 at DESY, Hamburg



LBNL
Howard Wieman, Eric Anderssen,
Hao Qui, Leo Greiner, Joe Silber

IPHC-Strasbourg
Michal Szelezniak

First operational vertex detector based on MAPS

MAPS developed by PICSEL group of IPHC-Strasbourg
(Marc Winter et al.)

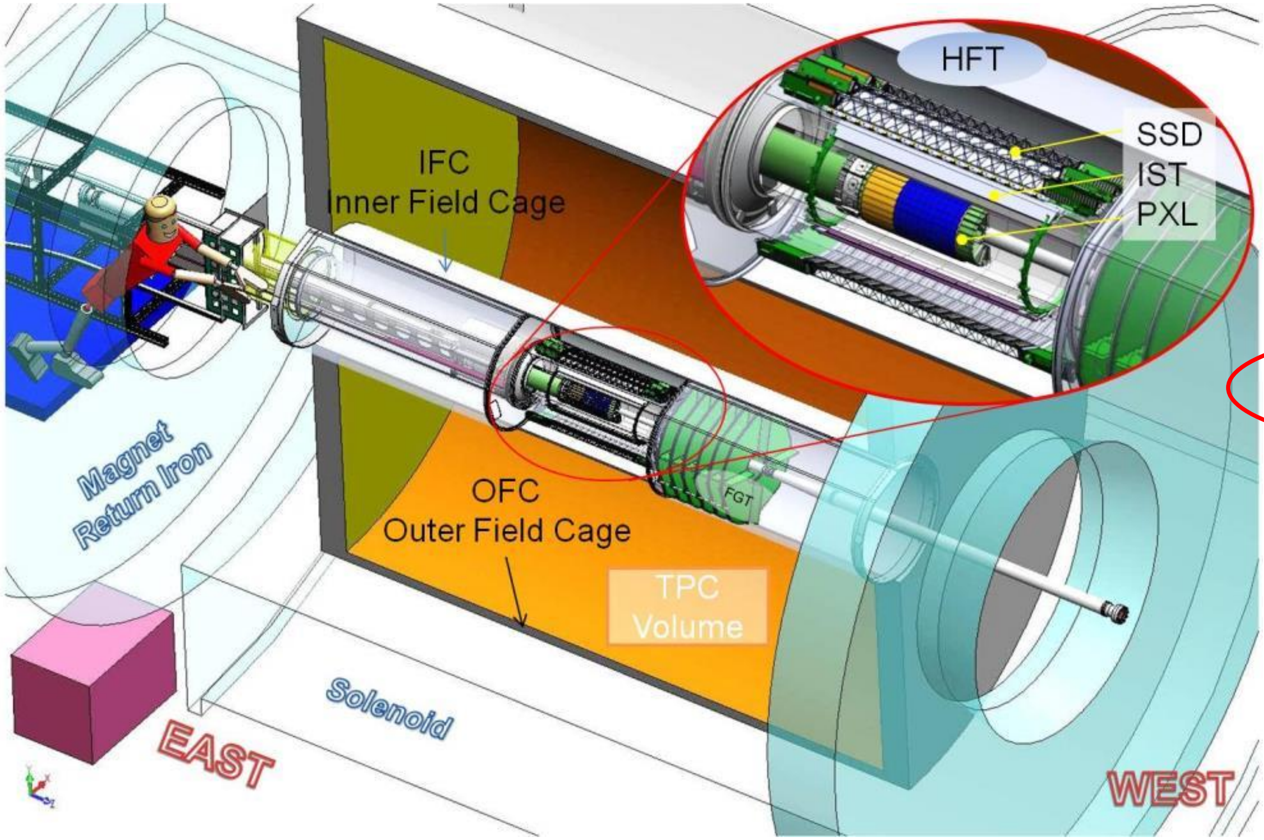
Outline

- Introduction to PXL detector in STAR with brief design description.
- The challenge of high resolution and low radiation length
- Mechanical work addressing:
  - Stability against thermal deformation
  - Air cooling
  - Stability against air flow induced vibration and deformation
  - Stability against external support vibration
  - Spatial mapping of the pixel locations
  - Rapid installation and replacement

i.e. how to avoid compromising high resolution potential of MAPS chips

HFT PXL in STAR Inner Detector Upgrades

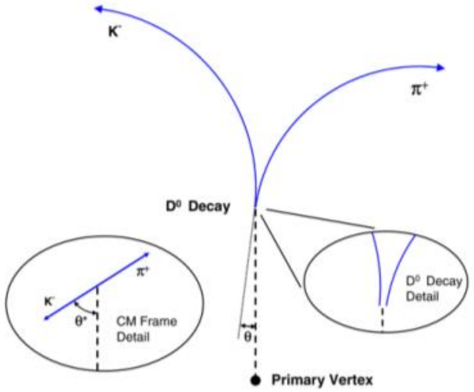
STAR HFT



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

HFT – Heavy Flavor Tracker

- SSD – Silicon Strip Detector
  - r = 22 cm
- IST – Inner Silicon Tracker
  - r = 14 cm
- PXL – Pixel Detector
  - r = 2.8, 8 cm



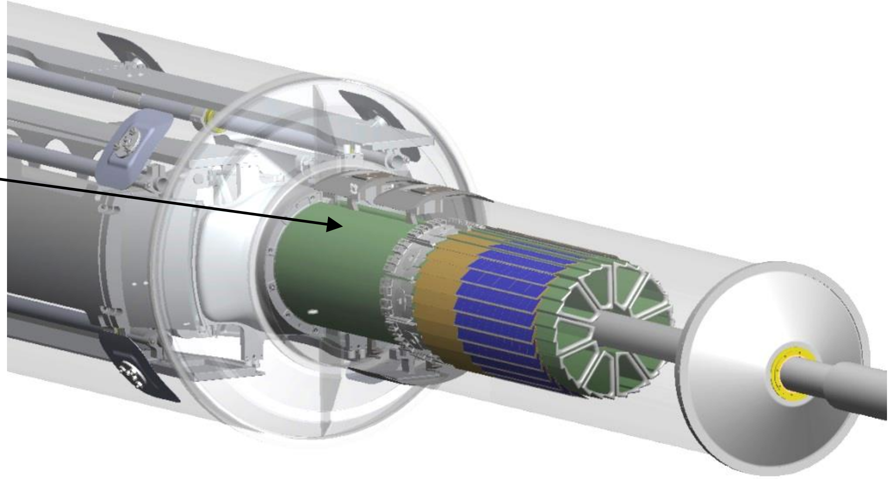
Direct topological reconstruction of Charm

We track inward from the TPC with graded resolution:

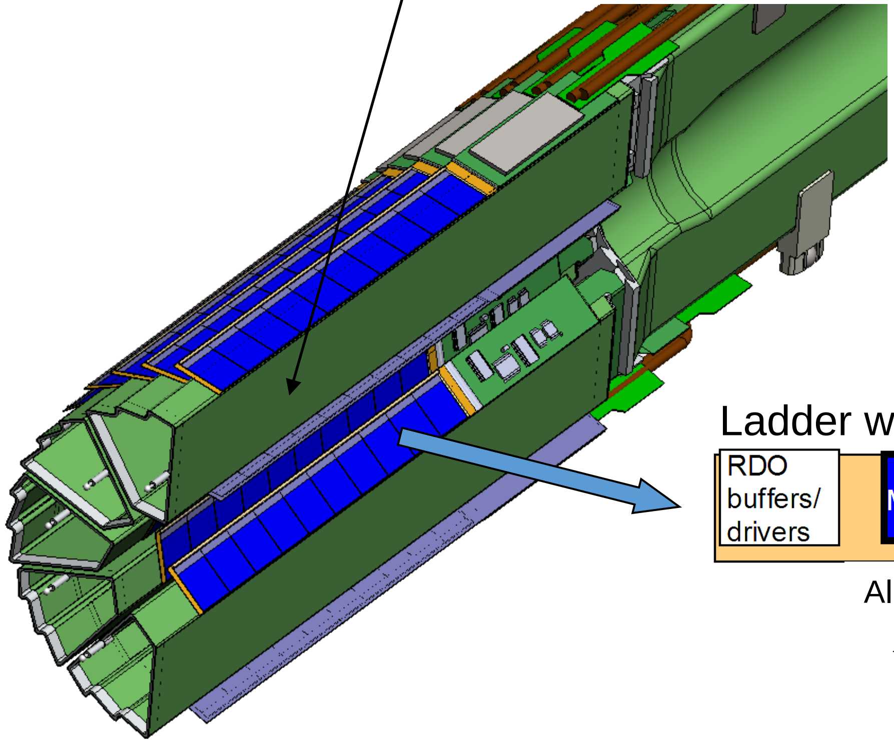
TPC → ~1mm → SSD → ~300µm → IST → ~250µm → PXL → <30µm → vertex

PXL Detector Design

Mechanical support with kinematic mounts (insertion side)

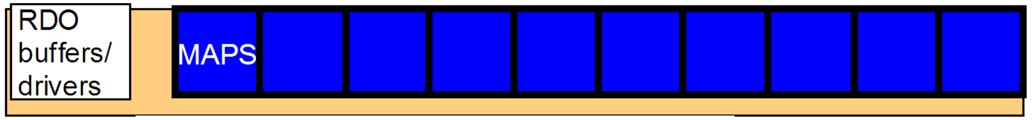


carbon fiber sector tubes (260 µm thick)



Insertion from one side
2 layers
5 sectors / half (10 sectors total)
4 ladders/sector
5 ladder weight 11.2 gm

Ladder with 10 MAPS sensors (approx. 2×2 cm each)



Aluminum conductor Ladder Flex Cable

20 cm

PXL Detector Design Characteristics

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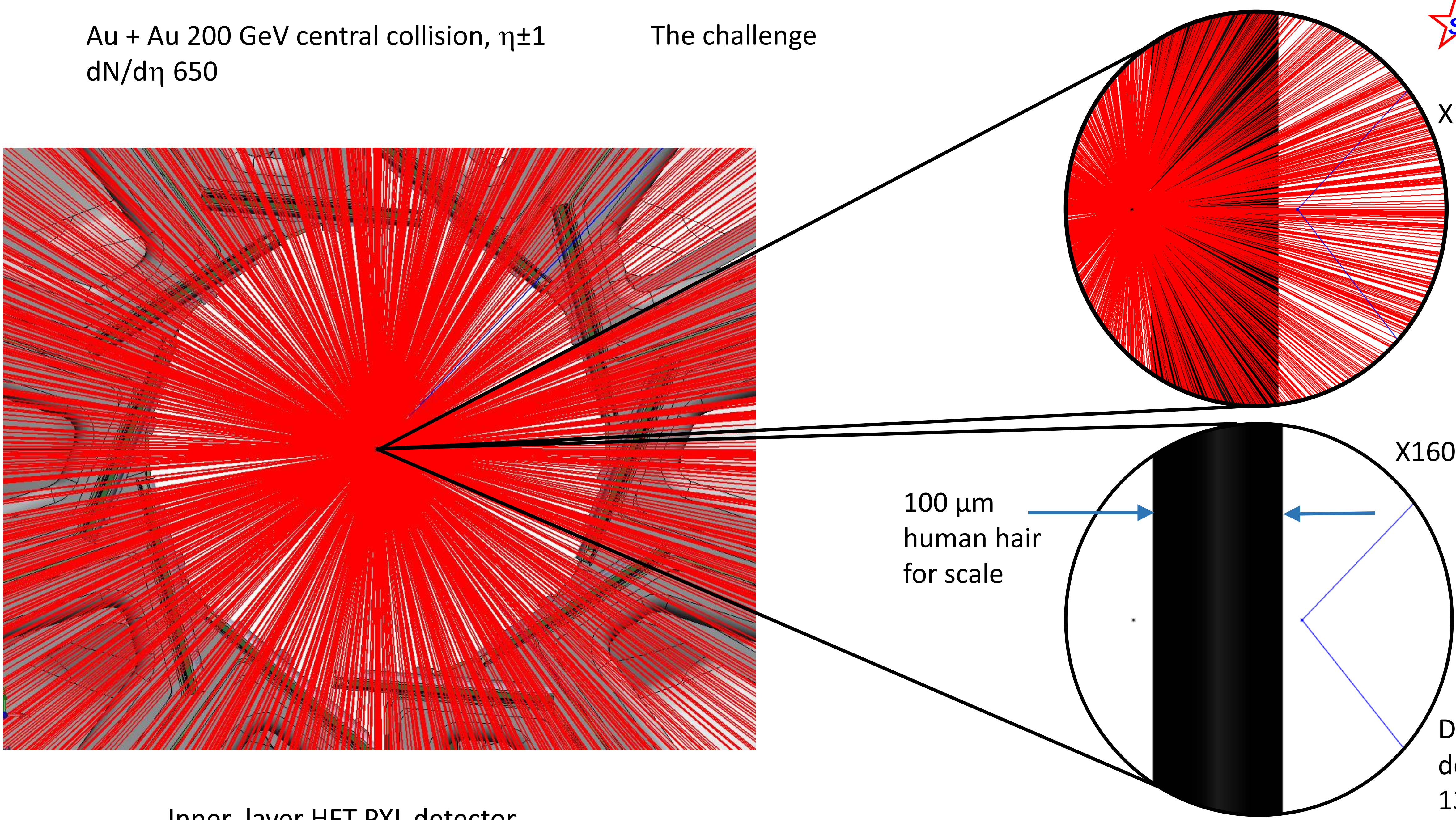
DCA Pointing resolution	(12* $\oplus$ 24 GeV/p·c) μm
Layers	Layer 1 at 2.8 cm radius Layer 2 at 8 cm radius
Pixel size	20.7 μm X 20.7 μm
Hit resolution	3.7 μm (6 μm geometric)
Position stability	6 μm rms (20 μm envelope)
Radiation length first layer	X/X_0 = 0.39% (Al conductor cable)
Number of pixels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

* Simple geometric component, cluster centriod fitting gives factor of ~1.7 better.

Au + Au 200 GeV central collision, η±1
dN/dη 650

The challenge



Inner layer HFT PXL detector

The advantage of improved spatial resolution and reduced radiation length

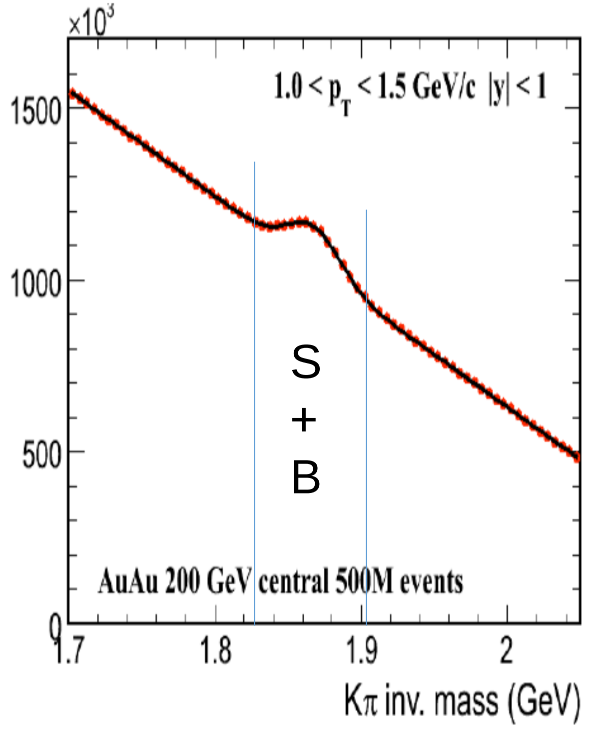
Compare simulated detector performance in number of events required to reach a given significance:

$$\frac{signal}{\sqrt{signal+background}}$$

Simulation results

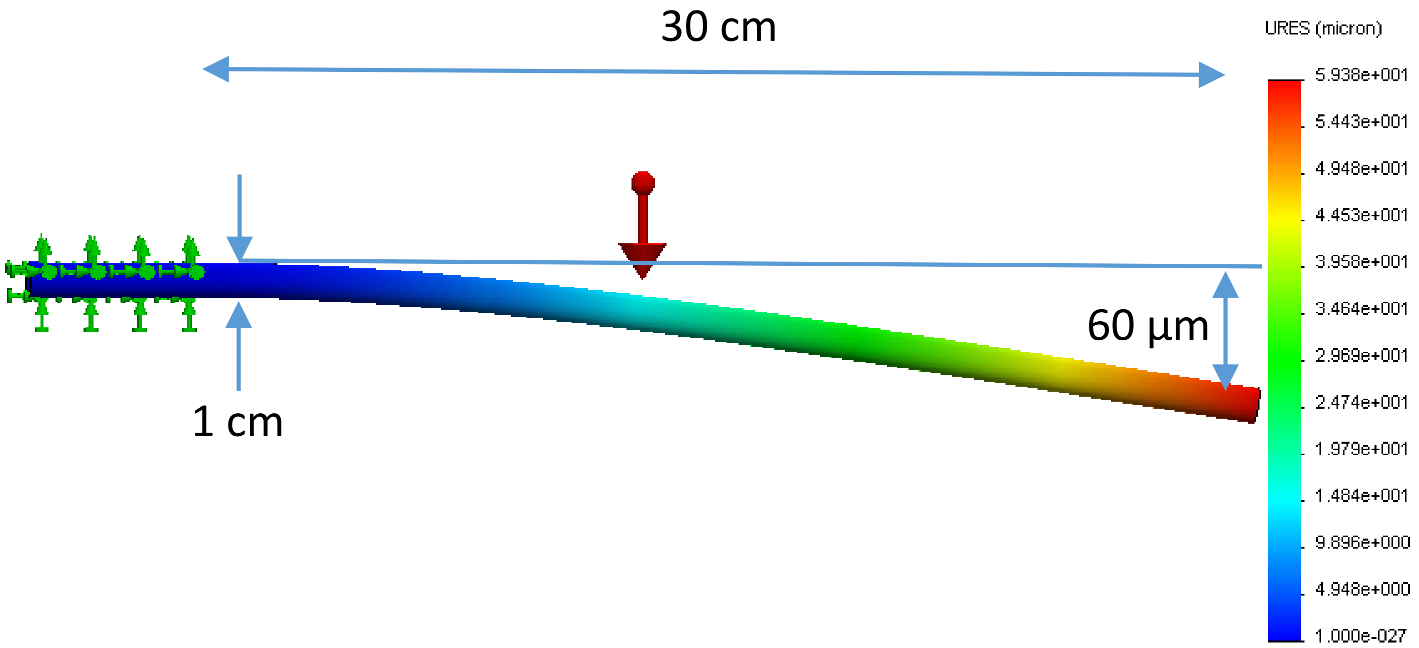
	Pixel size	radiation length	0.5 GeV D_0 relative number of events	1.5 GeV D_0 relative number of events
hybrid	50 μm x 450 μm	1.4%	36	200
MAPS	27 μm x 27 μm	0.6%	1	1

parameters used in the simulation, but actual HFT PXL parameters are smaller



Stability and reduced radiation length requirement makes for an interesting mechanical challenge

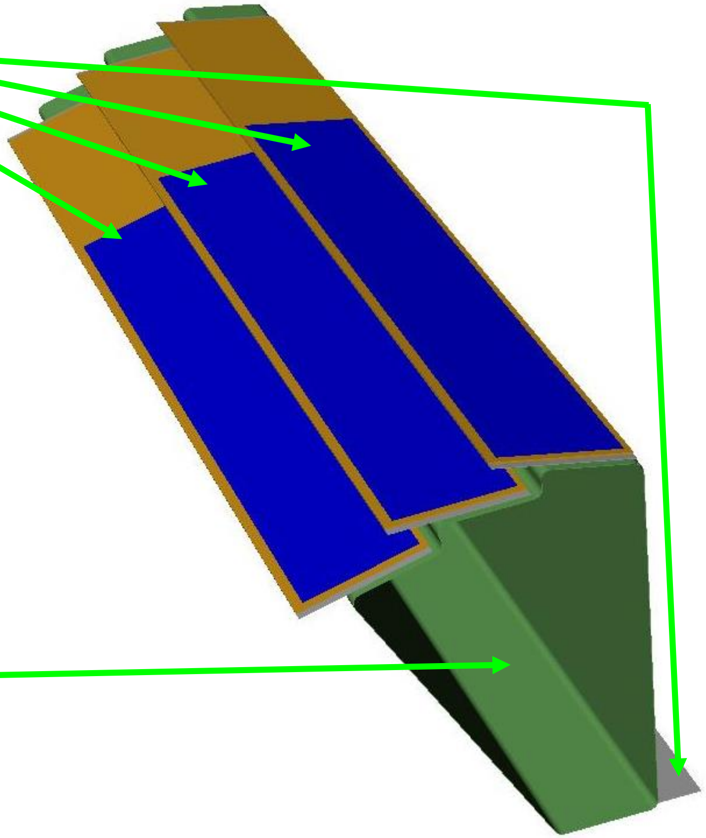
The MAPS pixels are 20 µm square on thinned (50 µm) silicon. The mechanical stability and alignment should not compromise this potential position resolution. And the mass of support structures should not compromise the potential reduced multiple coulomb achieved with thinned silicon.



To give a feeling for what 20 µm means mechanically, consider a 1 cm steel rod projected 30 cm. The sag due to gravity is 60 µm

Controlling thermal induced deformation

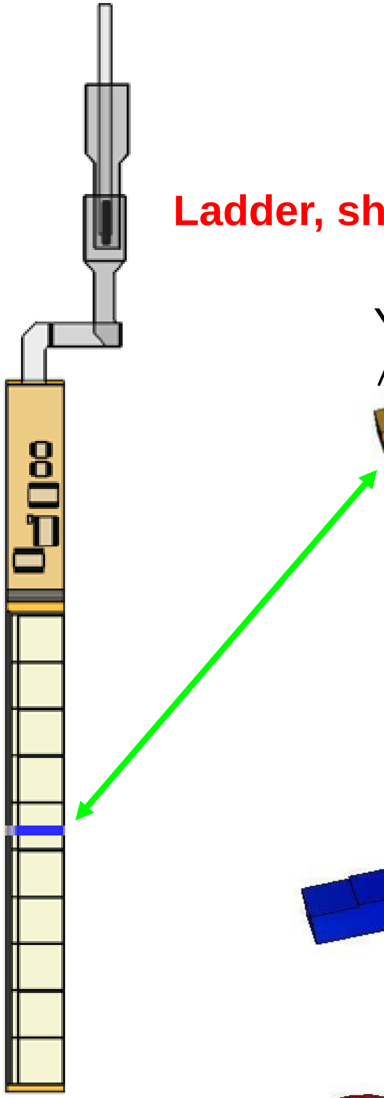
- The detector ladders are thinned silicon, on a flex kapton/aluminum cable
- The large CTE difference between carbon composite and kapton is a potential source of thermal induced deformation even with modest 10-15 deg C temperature swings
- Two methods of control
  - ALICE style carbon composite sector support beam with large moment of inertia
  - Soft decoupling adhesive* bonding ladder layers



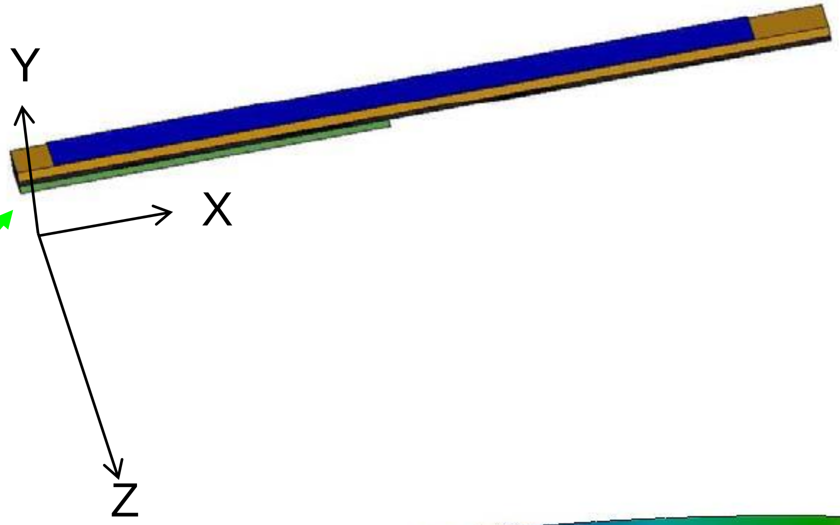
* 3M 467MP 200MP adhesive, acrylic 2 mil sheet, shear modulus 1.5x10^4 Pa (2 psi)

Considered other ladder and sector design structures, but this approach offered good stiffness to mass as well as good air cooling

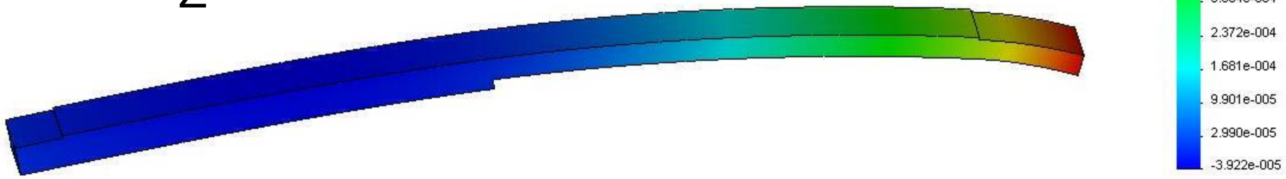
FEA analysis showing bi-metal thermally induced deformation



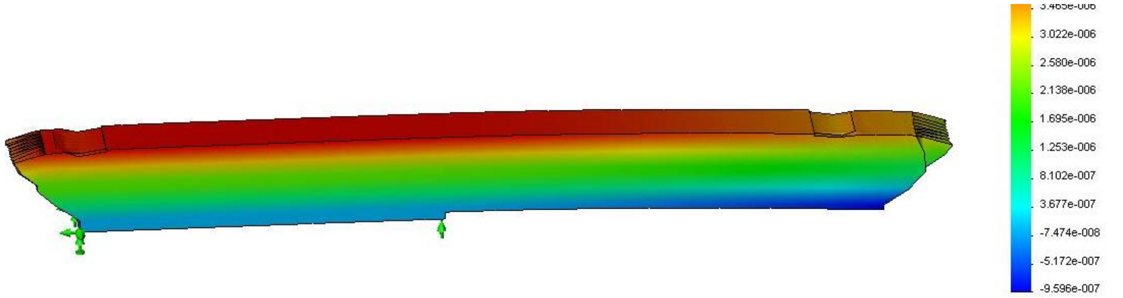
Ladder, short cross section analysis



20 deg C
temperature change



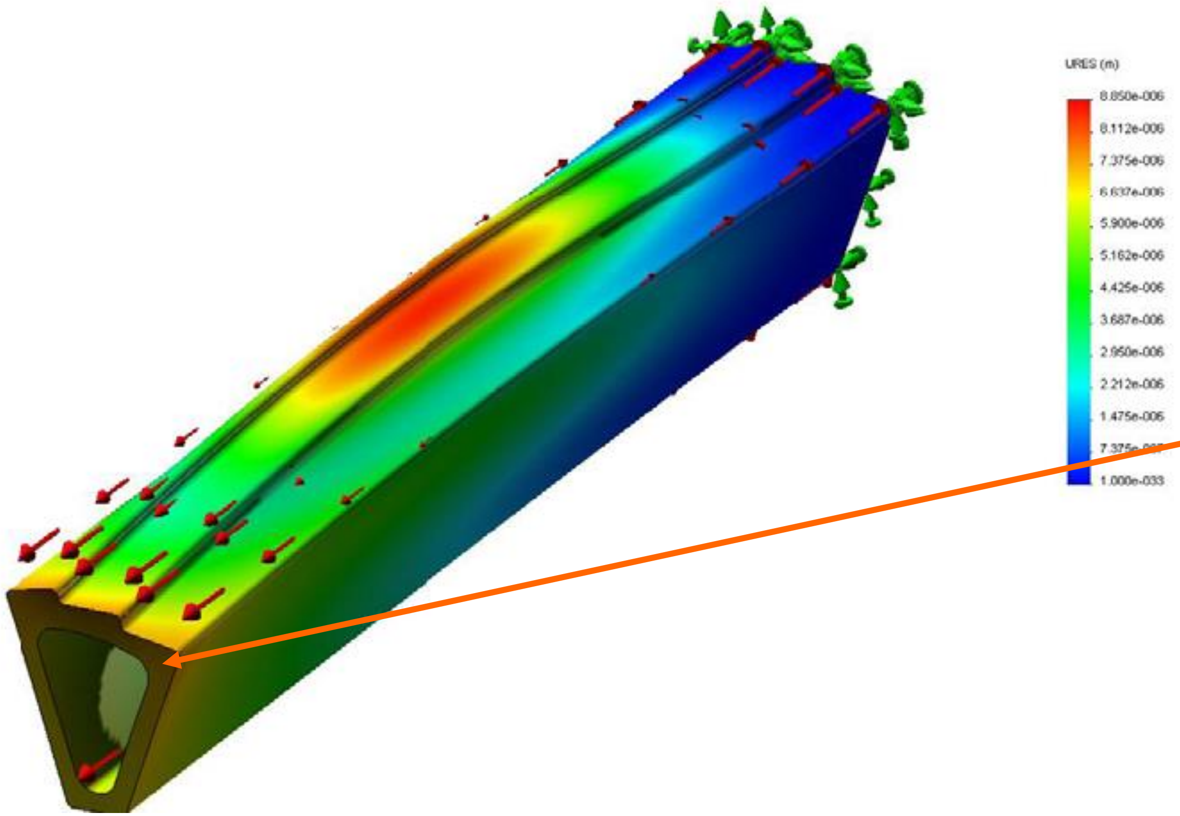
rigid bond
500 micron deformation



soft adhesive
4.3 micron deformation

Timoshenko, S. Analysis of bi-metal thermostats. J. Opt. Soc.Am. 1925, 11, 233-255,
if you don't want to take the easy way out with FEA

FEA analysis of thermally induced deformation of sector beam

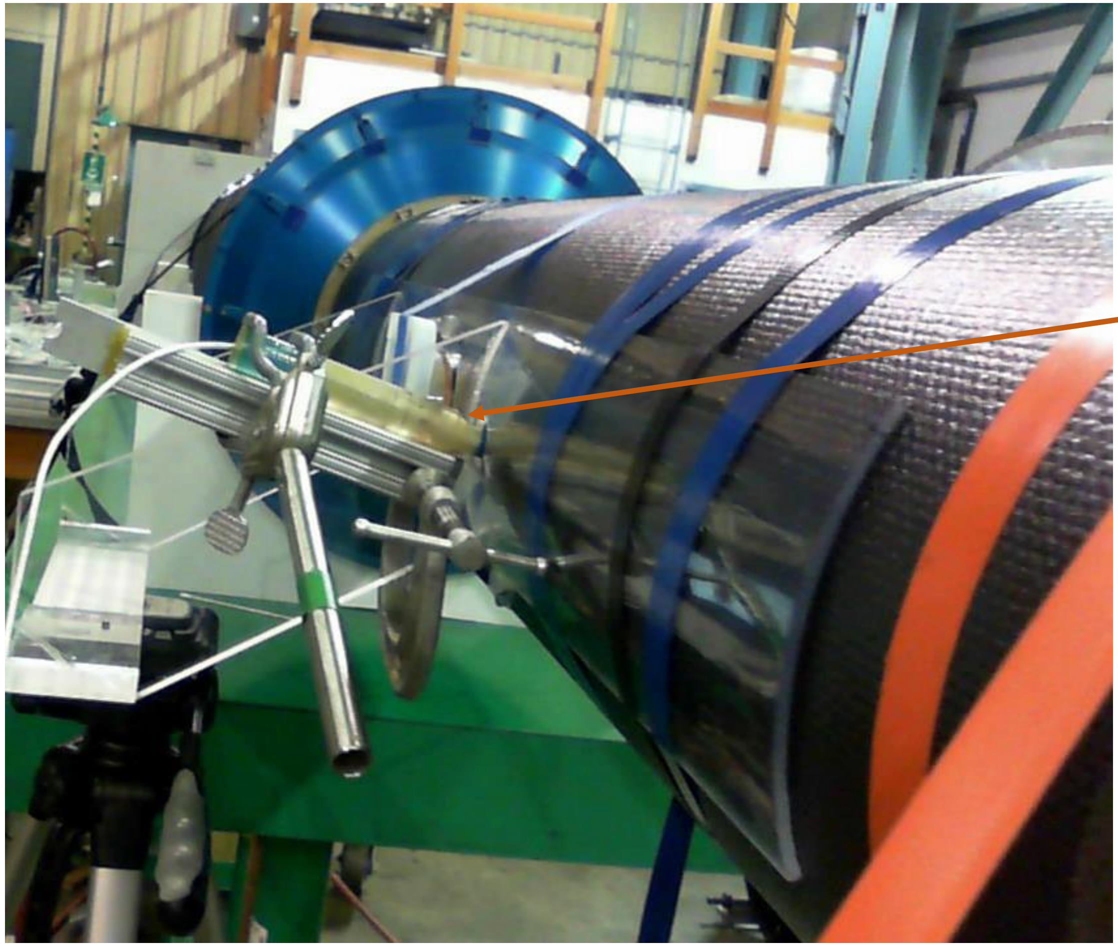


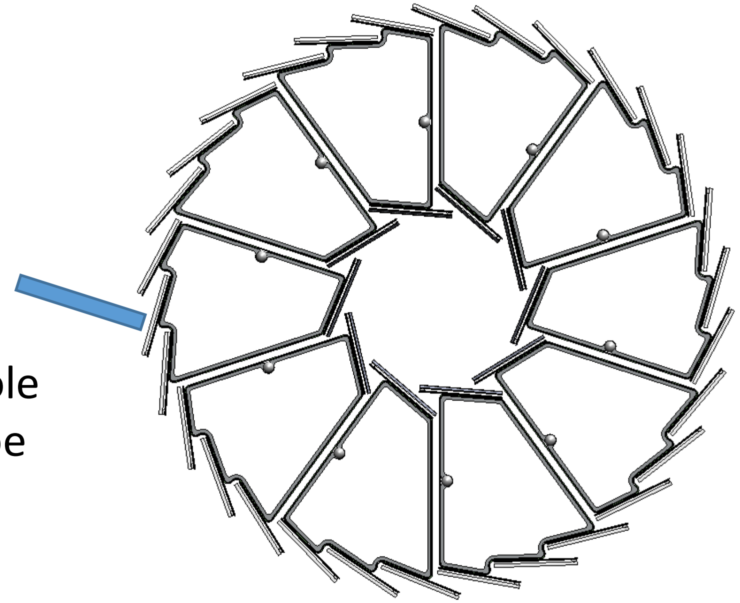
- FEA shell elements
- Shear force load from ladders
- 20 deg temperature rise
- Soft adhesive coupling
- 200 micron carbon composite beam
- end cap reinforcement
- Maximum deformation 9 microns (30 microns if no end cap)

Final measurement of thermal deformation with completed system.

probe:
Lion Precision
Model: C1-A
500 μm range
2.0 nm RMS resolution
http://www.lionprecision.com/

Same setup used to measure vibration and air pressure displacement, more on this to follow





capacitive probe inserted through hole in Pixel Support Tube (PST)
at z=~12 cm, this is on sector beam just past active ladder

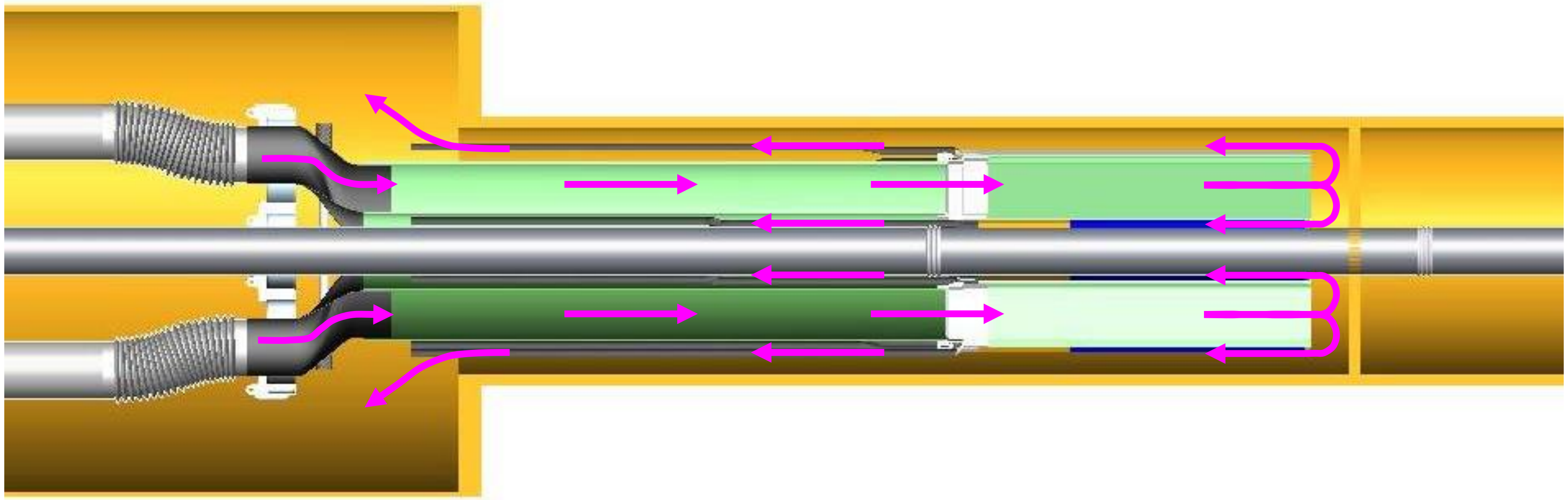
North half sectors populated with operating ladders. South half populated with empty sector tubes. System operated with full cooling air

Position change between sector power off and on

ladder moves
3 μm to 8 μm
toward center when powered (~10 °C change)

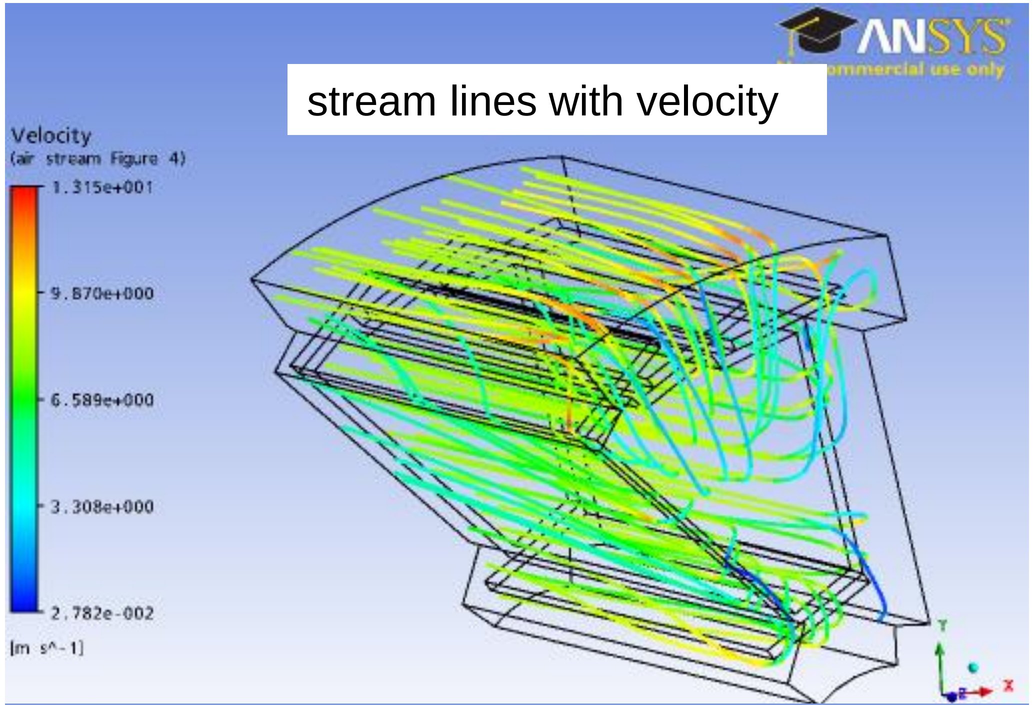
Air cooling of silicon detectors - CFD analysis

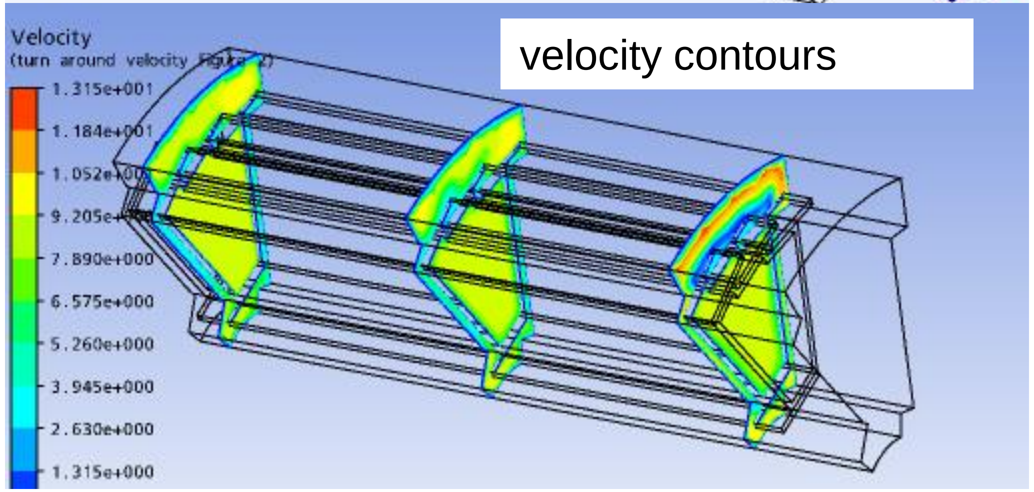
- Silicon power: 100 mW/cm^2 (~ power of sunlight)
- 240 W total Si + drivers



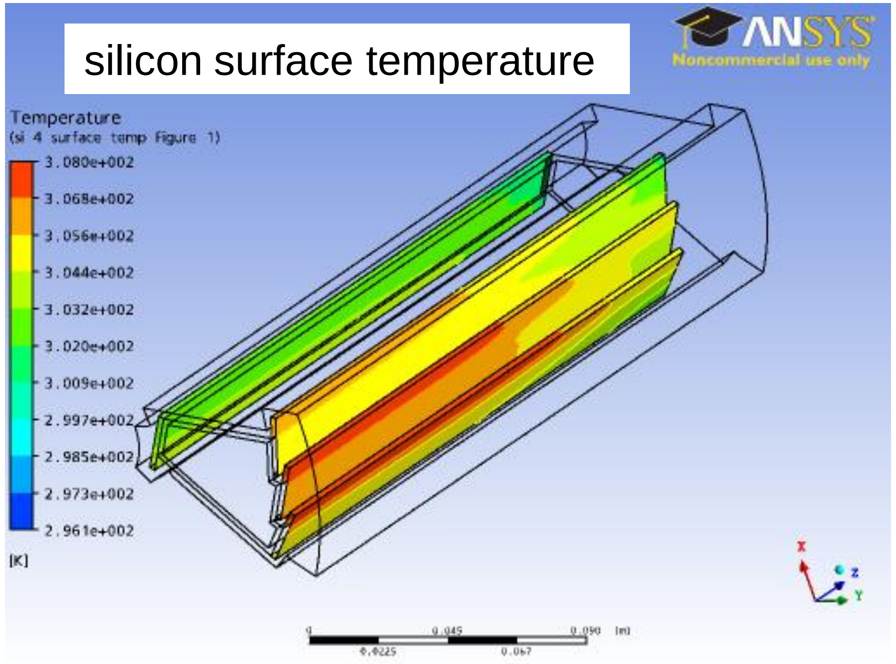
air flow path – flows along both inside and outside surface of the sector

Air cooling – Computational Fluid Dynamics (CFD) analysis

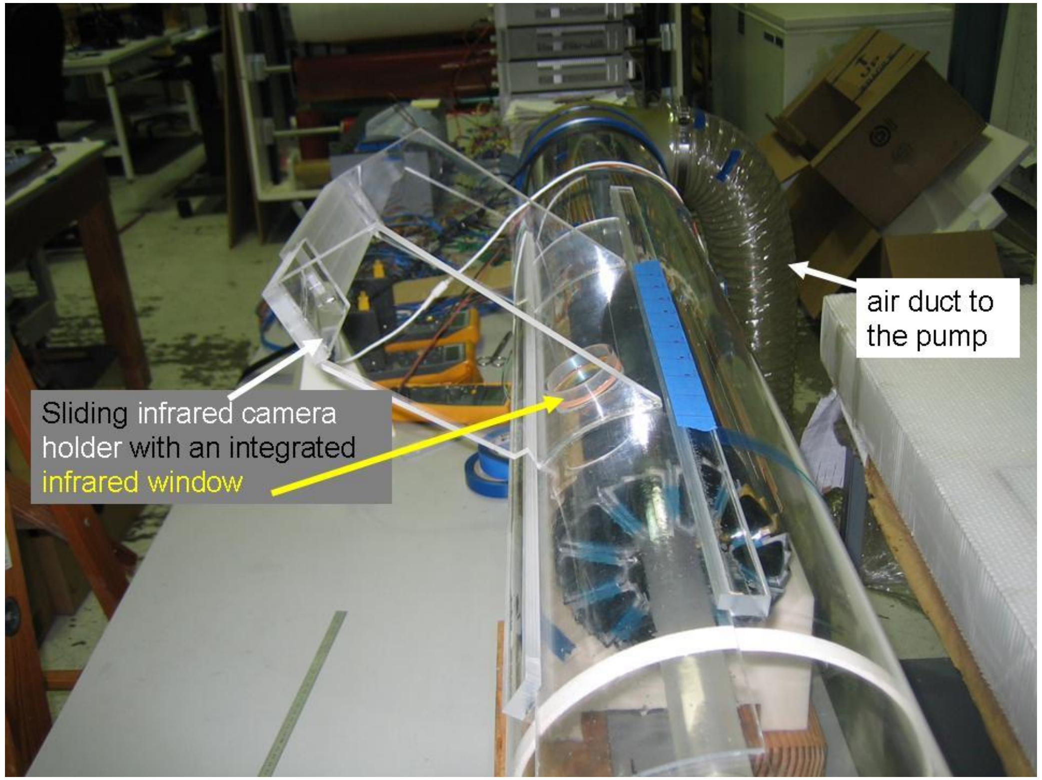




- air flow velocity 9-10 m/s
- maximum temperature rise above ambient: 12 deg C
- sector beam surface – important component to cooling
- dynamic pressure force 1.7 times gravity

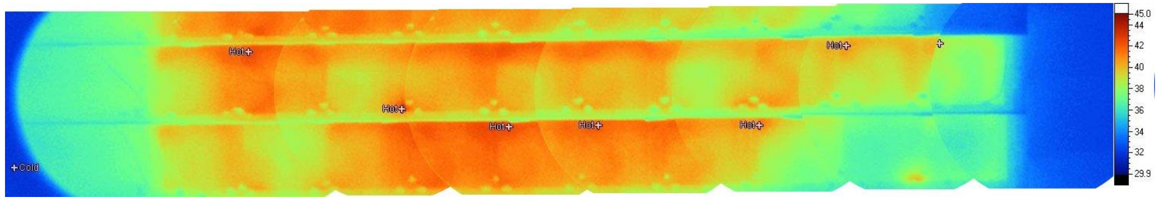


Full scale mockup to verify cooling capability



- 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

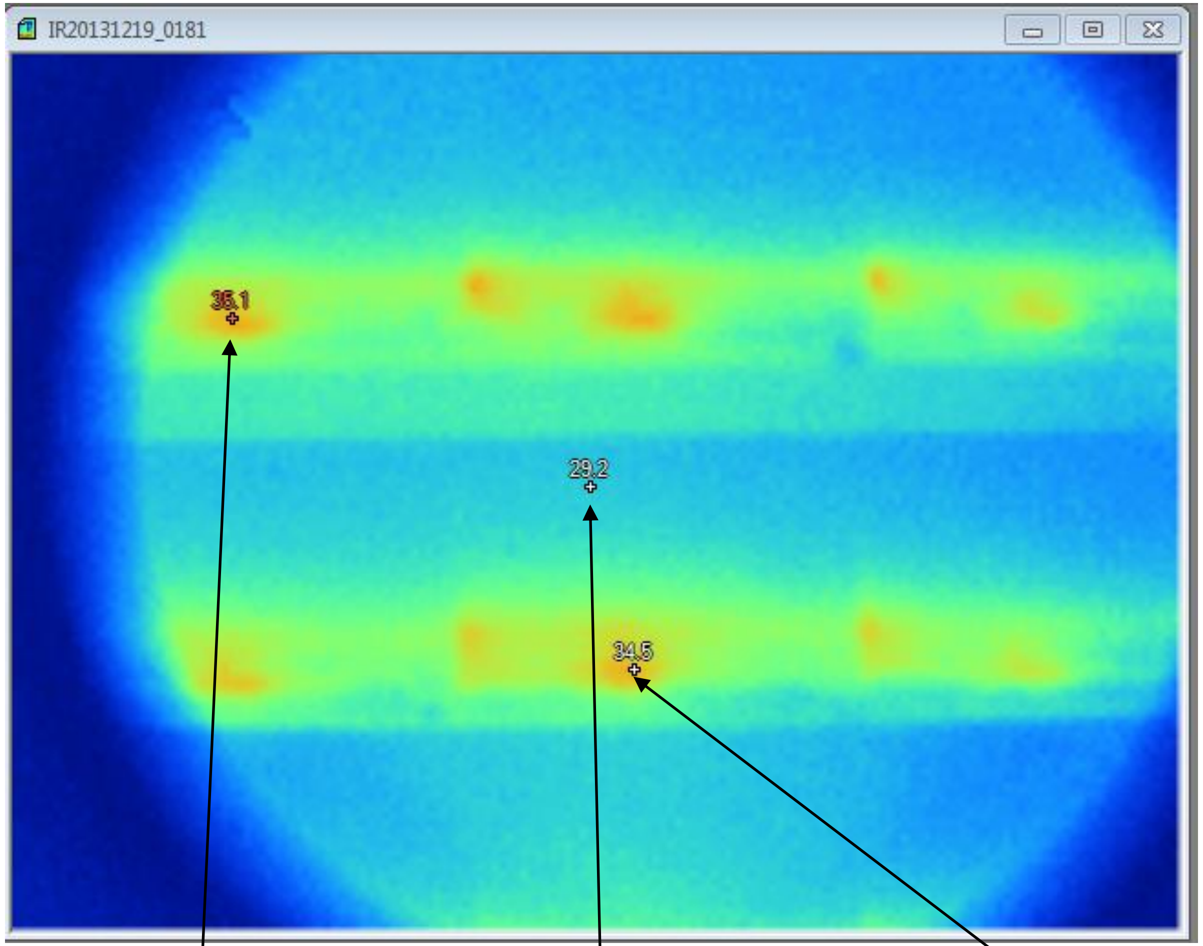
In these tests we failed to get good total mass flow measurements which complicated specifying the final cooling blower system.



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

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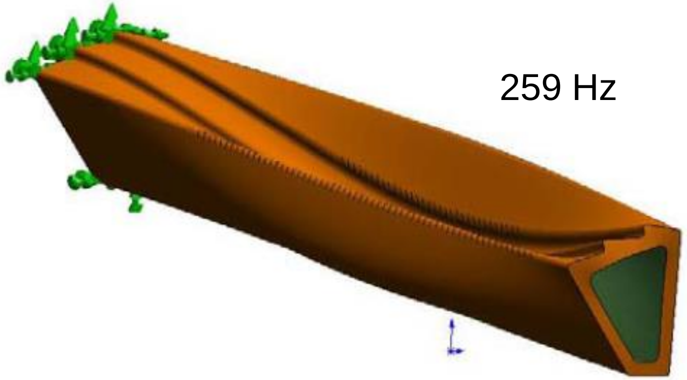
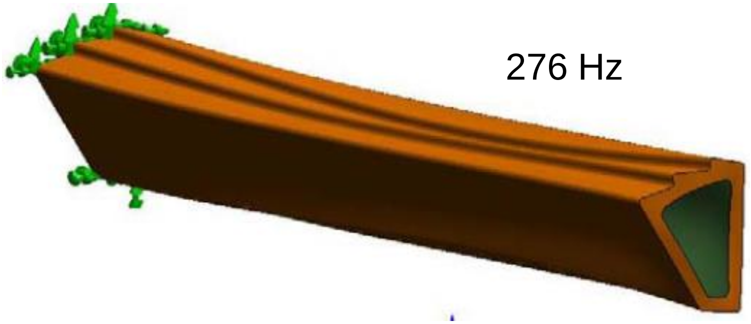
12 °C
MAX deviation from ambient

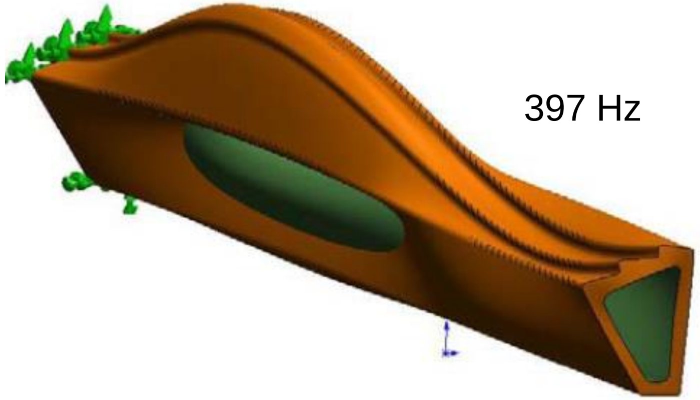
Static displacement and vibration induced by cooling air flow

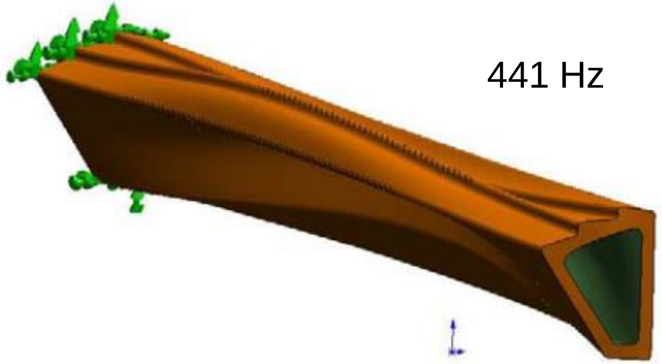
- Sector vibration modes were examined with FEA
- Prototype sector vibrations measured with airflow tests. This was determined to be less time consuming than setting up transient CFD calculations.
- Measurement of completed detector

vibration modes


259 Hz

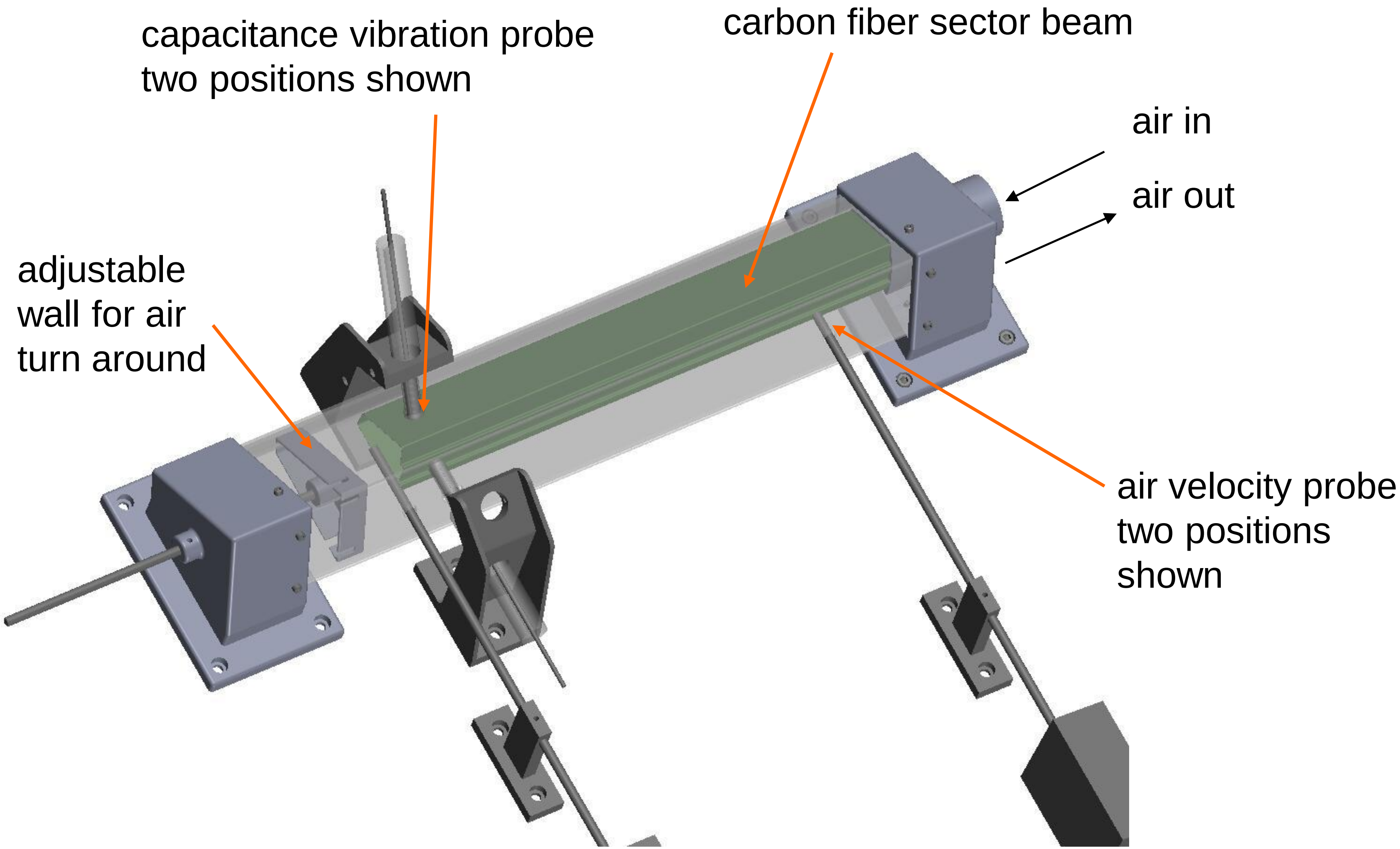

276 Hz


397 Hz


441 Hz


497 Hz

- Lots of complicated modes close in frequency wind tunnel setup to test vibration and displacement



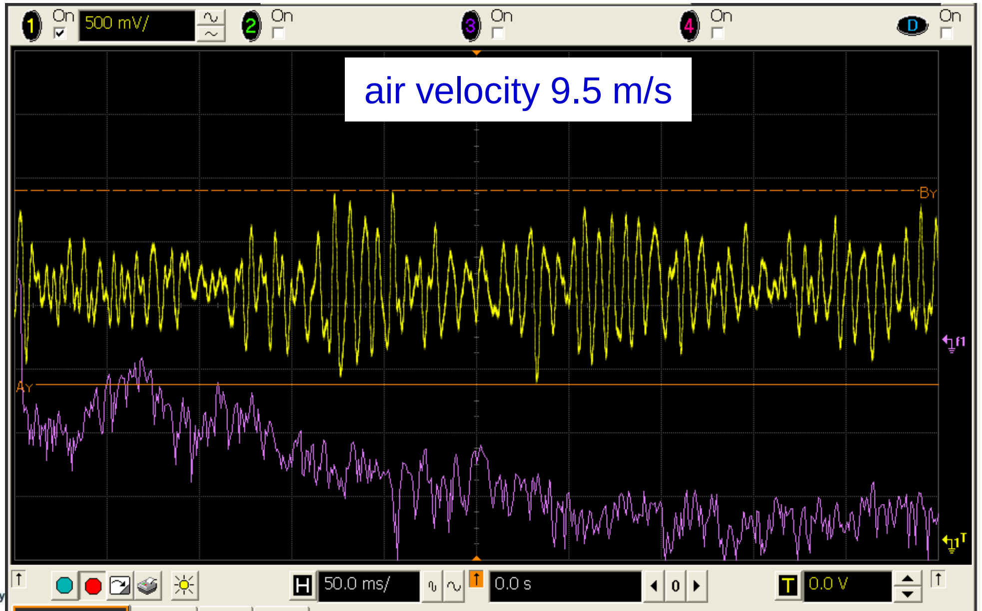
C:\Documents and Settings\Howard Wieman\My Documents\aps project\mechanical\PXL phase 1 sept 2008\sector ph1 wind tunnel.SLDASM

capacitive probe vibration measurements

proto type sector
wind tunnel test

4 μm

log FFT, peak at 135 Hz

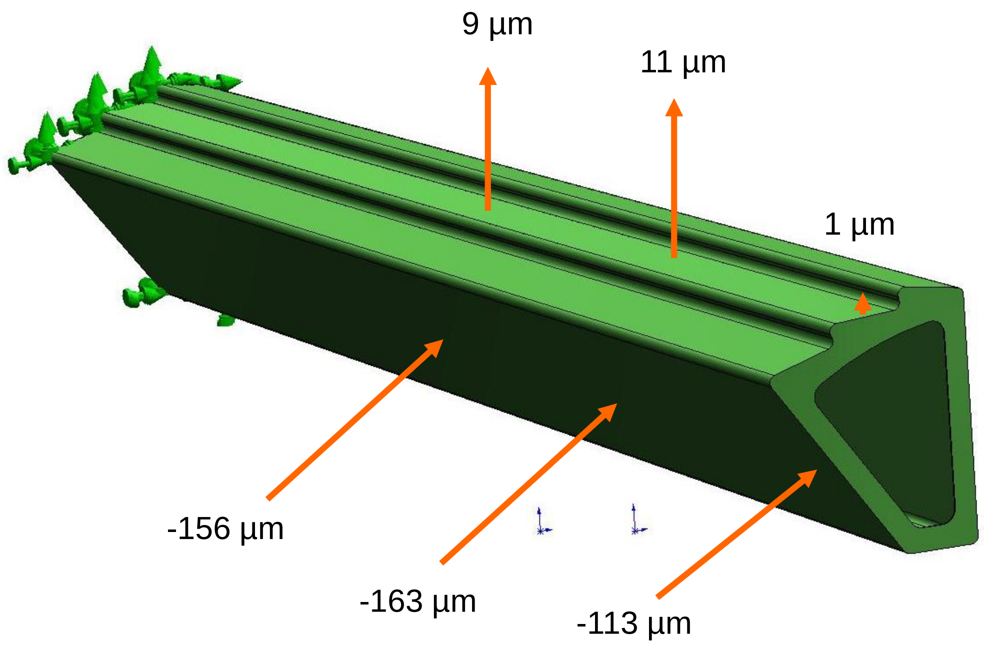


38 μm

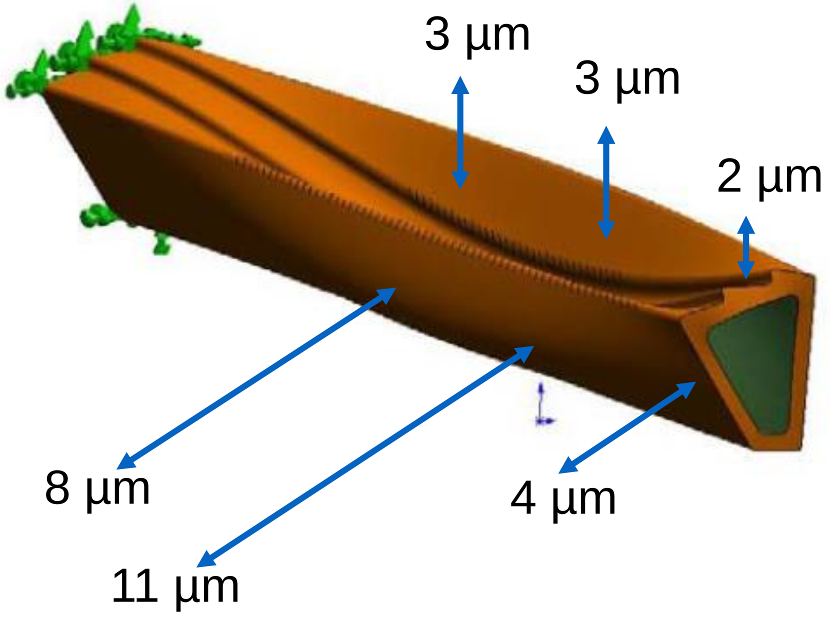
effect of 9 m/s air flow

proto type sector
wind tunnel test

shapes of simulated 1st vibrational mode shown for qualitative comparison only



static deformation



vibration (RMS)

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

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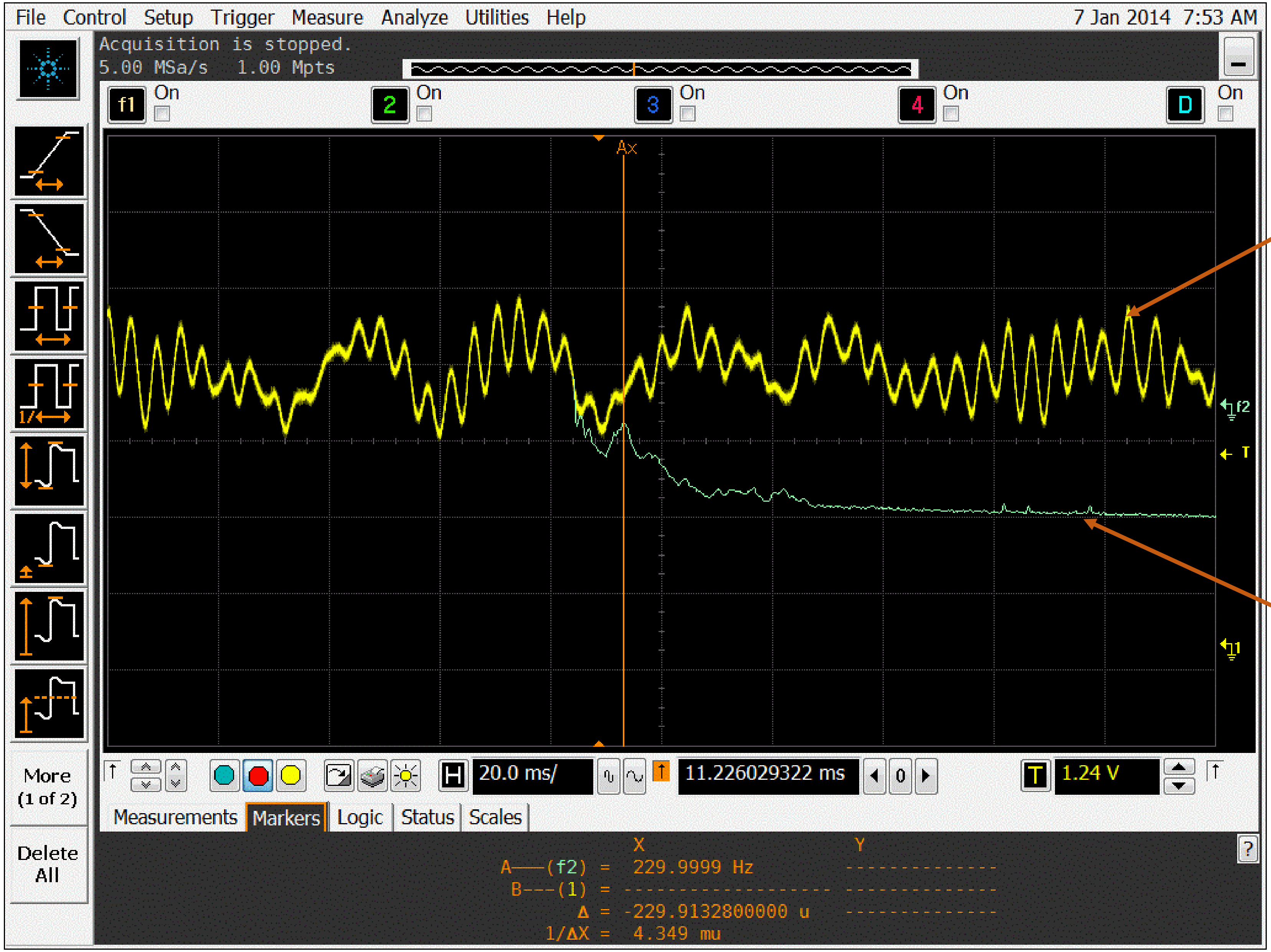


Probe signal

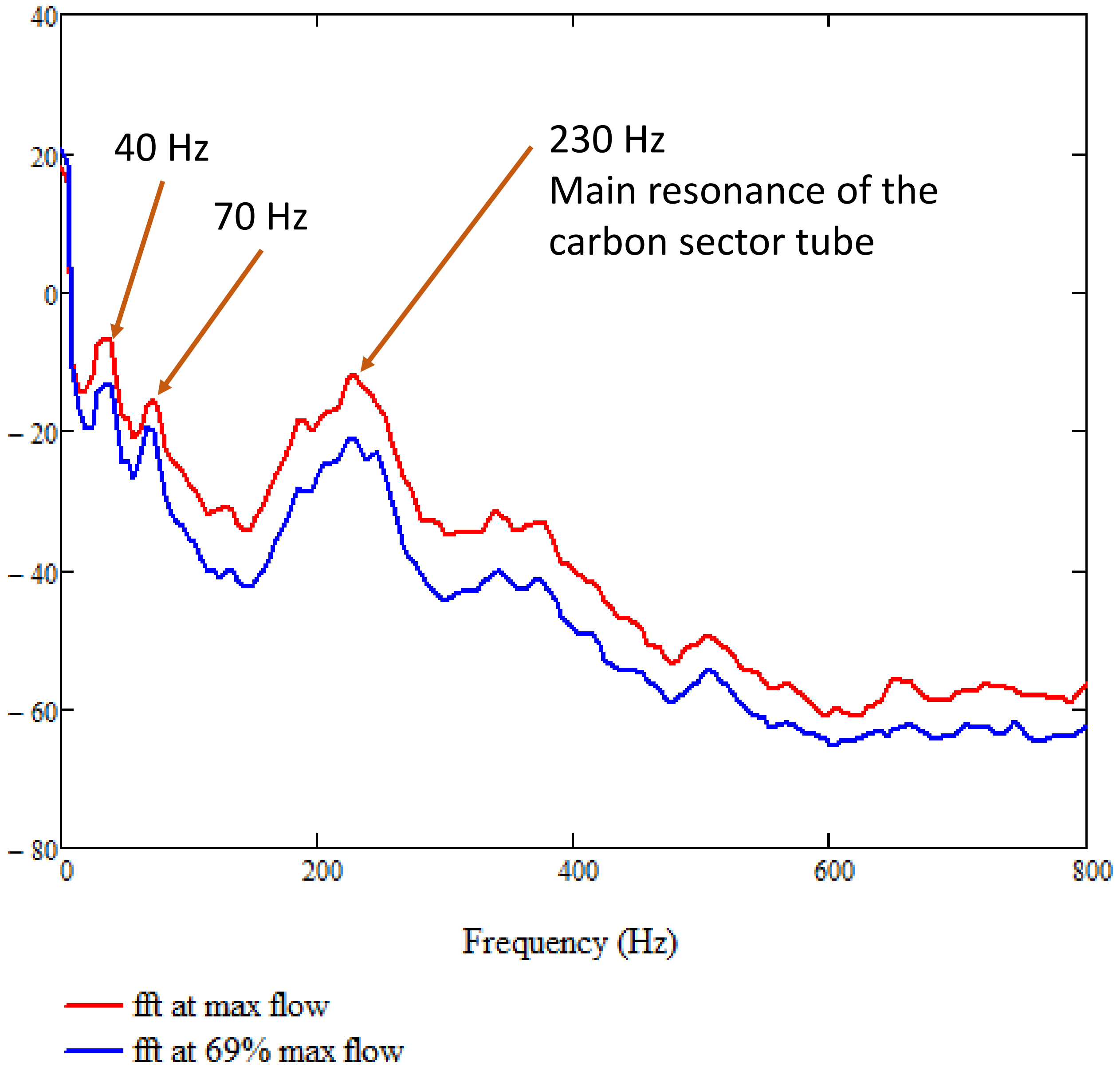
Stdev = 5 μm

Probe conversion = 1 μm/0.04 V

FFT, see next page for more detail

Fourier transform of sector vibration

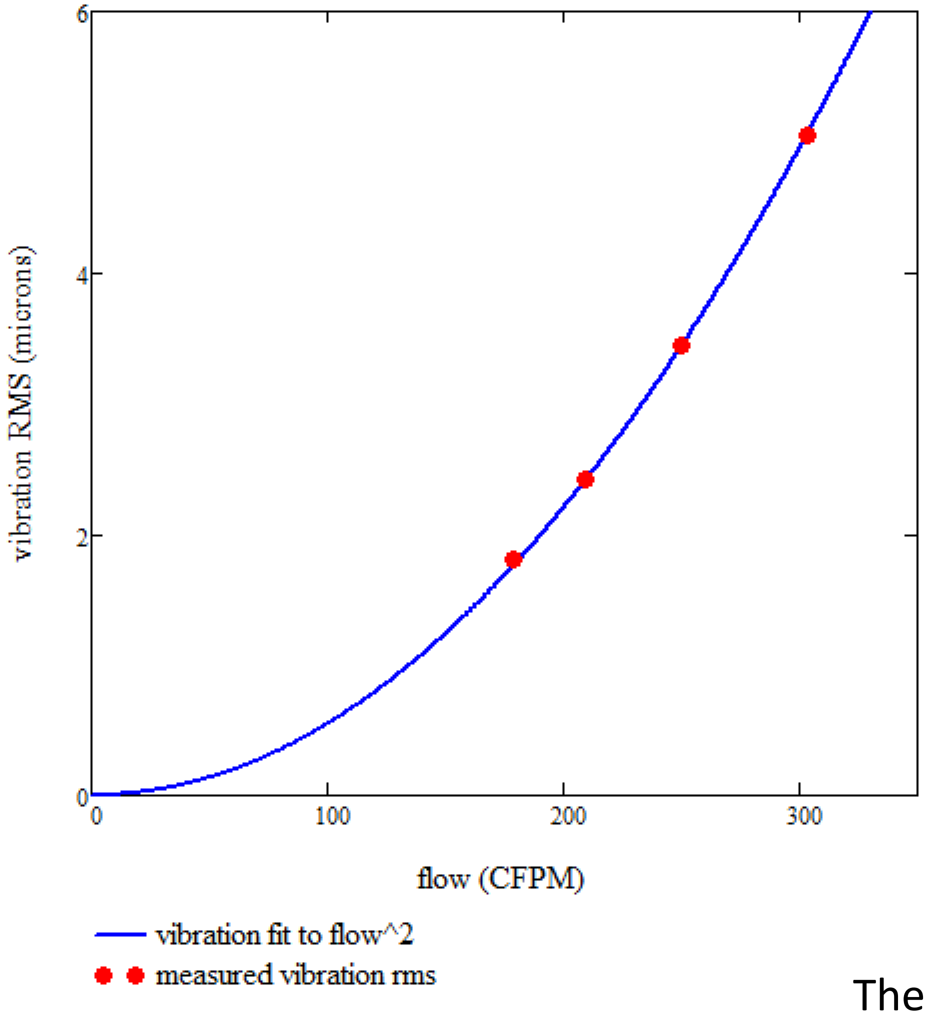
capactive probe measurement of completed PXL detector



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

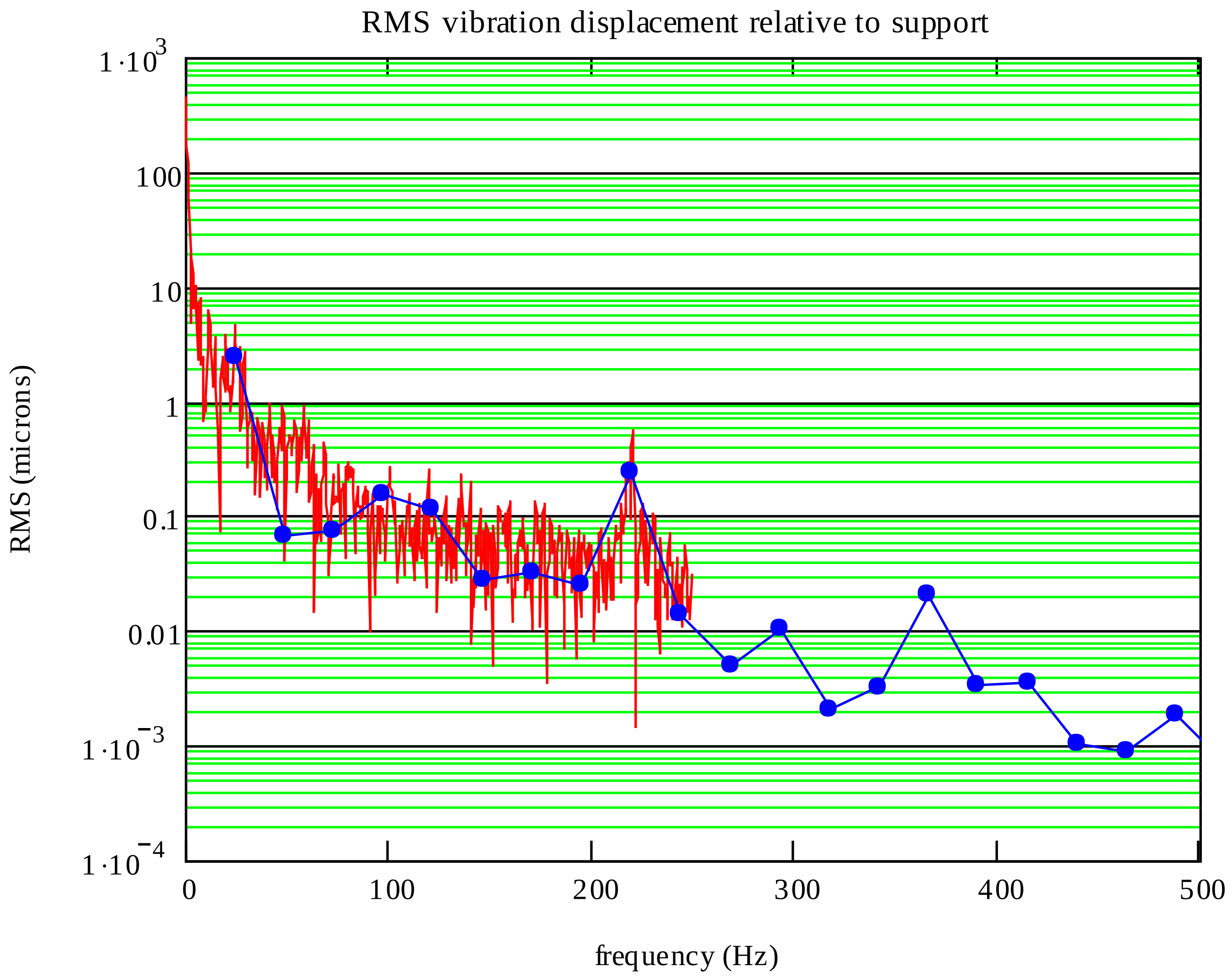


The measured vibration with no air flowing: 35 nm RMS capacitive probe measurement of completed PXL detector

cooling air induced vibration and static displacement

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 at full flow:	25 µm - 30 µm

Vibration from STAR support, accelerometer measurement



Early in the project an accelerometer was mounted on the support point in STAR while STAR was operating with the magnet on to determine if support vibration could affect the PXL pointing resolution.

The vibration magnitude is assessed for a harmonic oscillator driven by the acceleration power spectrum.

- detector vibration from STAR support < 0.1 micron RMS

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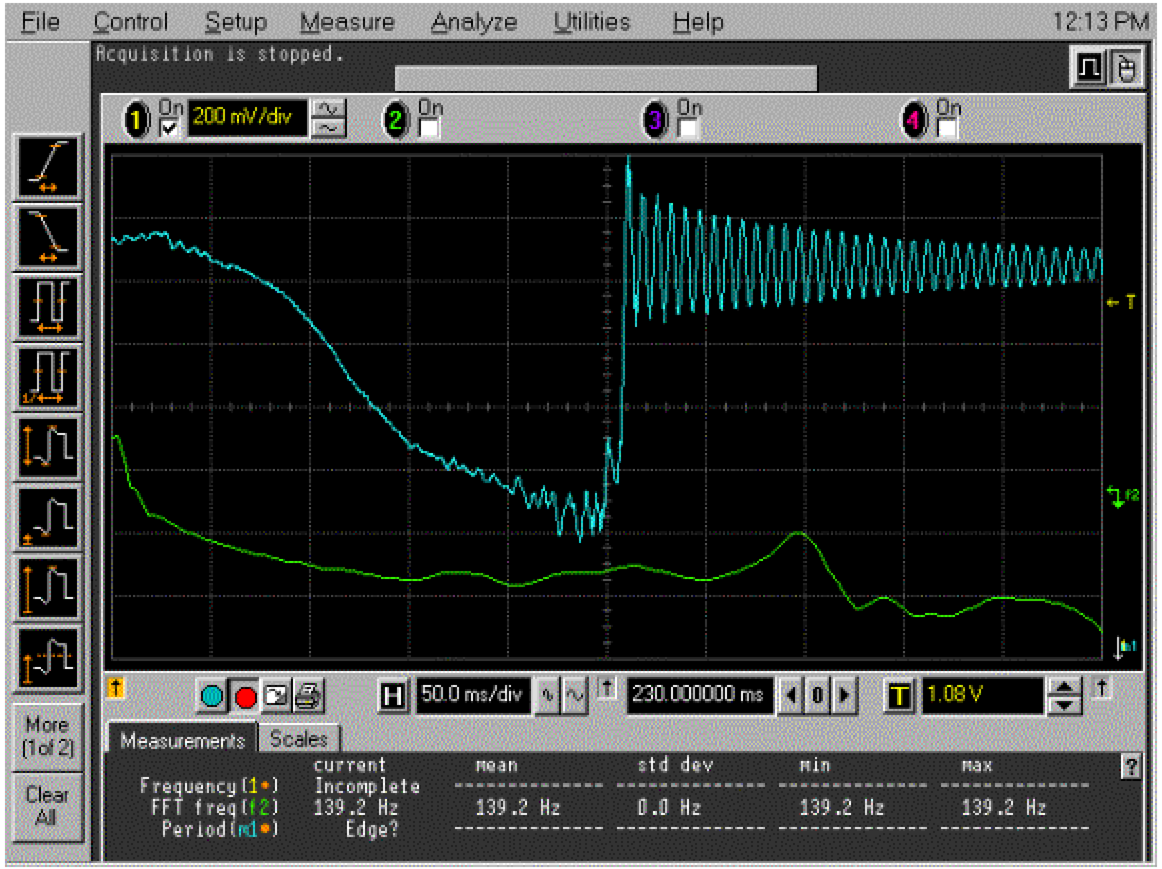
For this analysis used an earlier ladder prototype. The study was not updated with the final sector design because it was clear that this external vibration effect was not important

Resonance frequency and Q, damping obtained from capacitive probe measure of the ladder vibration as it decayed



If a harmonic oscillator mechanical structure is mounted on a vibrating support the RMS displacement relative to the support is given approximately as:

$$Zrms = \sqrt{\frac{\pi \cdot Q}{2} \cdot \frac{PSD(\omega)}{\omega^3}} \qquad [1]$$

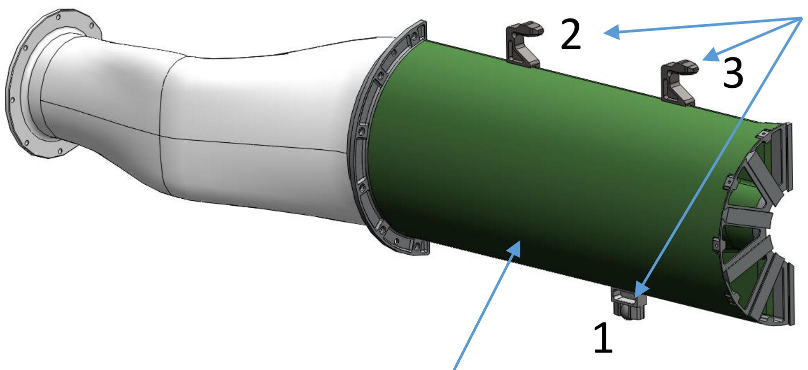
where
ω is the radial resonant frequency of the oscillator
$PSD(\omega)$ is the acceleration^2 density at the resonant frequency
and Q is the Q of the oscillator.

References:

1. Eq. 11.38 from "Shock & Vibration Handbook, Vol 1. Basic Theory & Measurements", Harris & Crede, 1961 McGraw-Hill, Library of Congress card catalogue number 60-16636

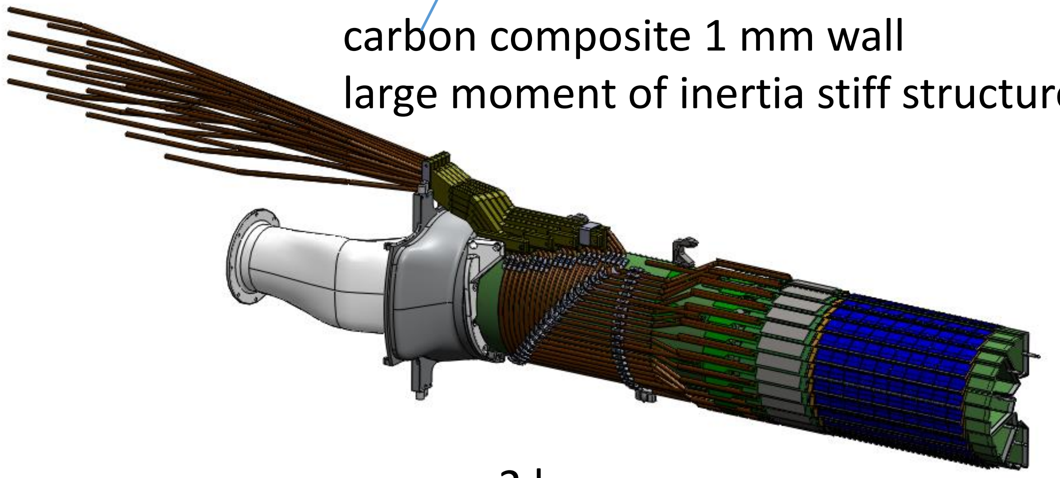
accelerometer:
Endevco
Model 86
Seismic accelerometer
https://www.endevco.com/

PXL support structure control of external forces



kinematic support points

carbon composite 1 mm wall
large moment of inertia stiff structure



2 kgm

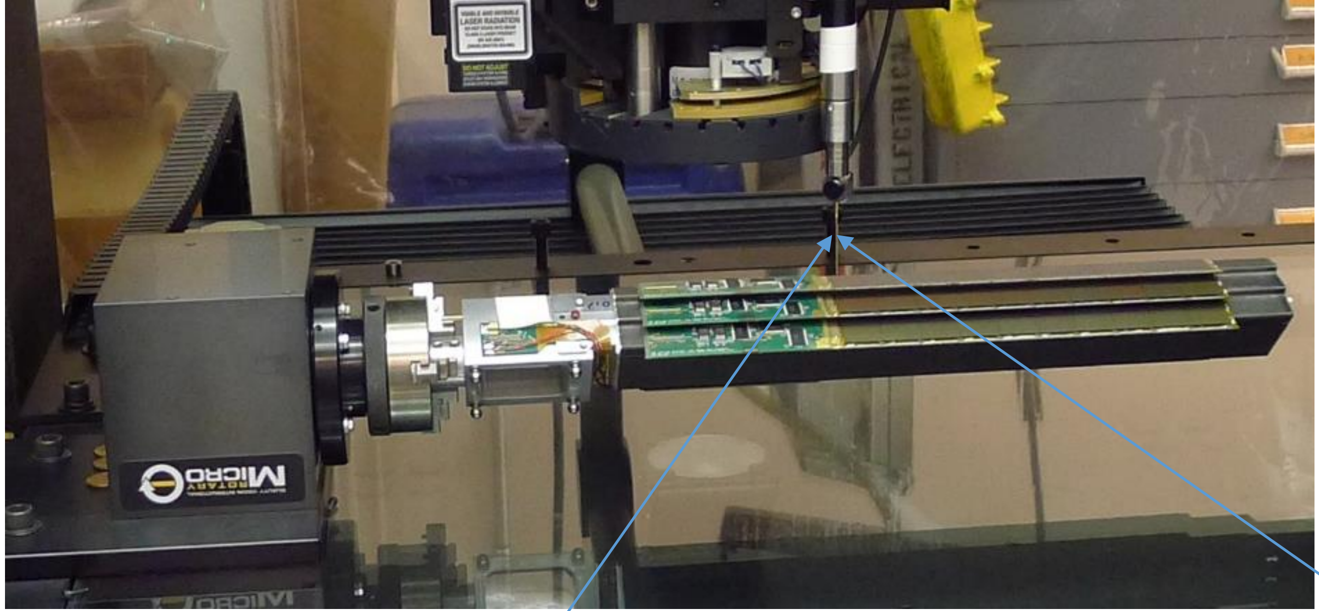
load source	load (kgf}
gravity	2
possible dynamic air pressure 10 m/s	0.5
signal cable stiffness, controlled using very fine twisted pairs, 160 μm wire.	negligible
power cable stiffness, multi conductor 130 μm strands	negligible
flexible air ducting	unknown

Early FEA analysis showed sub micron distortions, but no analysis done with final loads and design details.

Could not find easy analysis for flexible air ducting to cover reaction to air velocity changes and air frictional forces.
Decided to address decoupling after construction if a problem was found, dogged a bullet on this one.

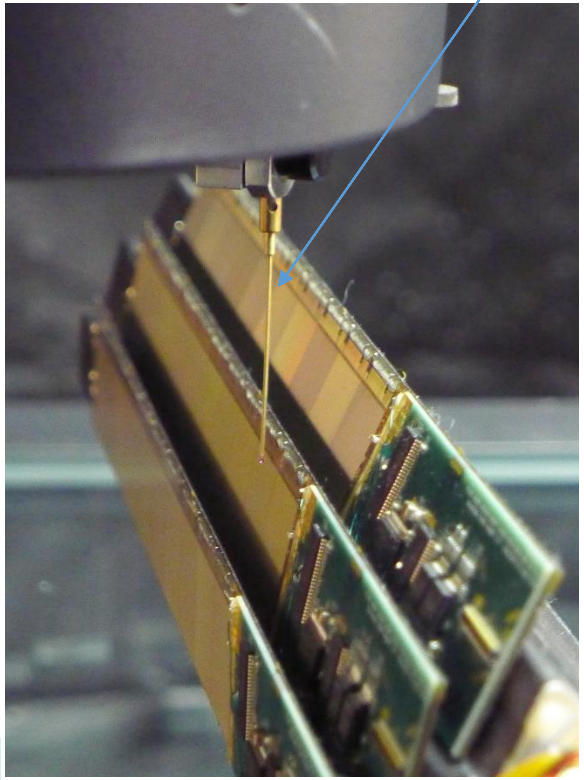
Spatial mapping of the pixels

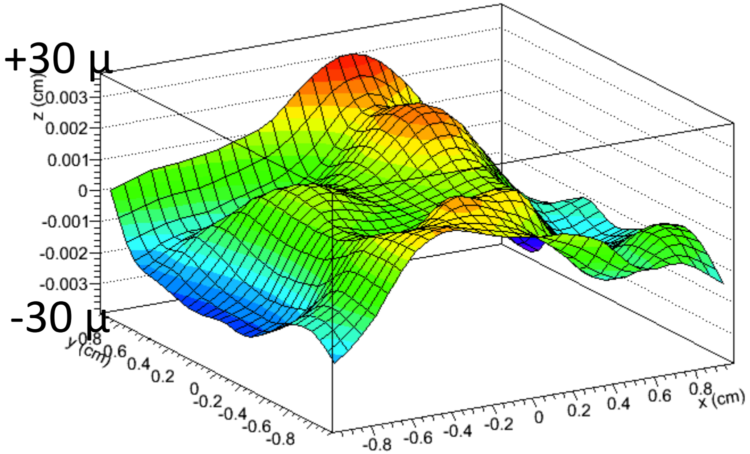
Pixel locations determined with CMM equipment to within 10 μm prior to installation in STAR



Programmed CMM Measurement method#:

- All pixels located on a sector with respect to 3 sector tooling balls
  - 2 Lithography points on the chips measured with optical head
  - Chip surface profile measured with 11 x 11 point pattern using a Feather Probe*. Using a touch probe permits picking up over hung surfaces

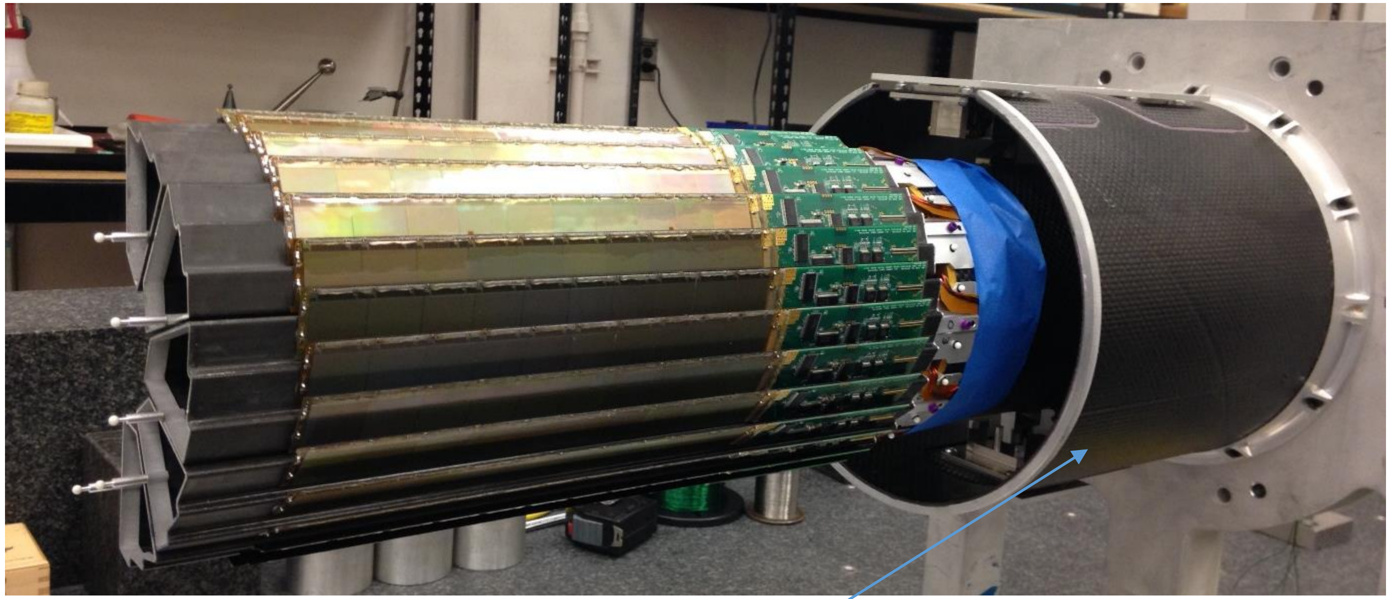




PXL sensor surface profile from survey: ± 30 μm > PXL hit error,
and the chip to chip surface deviation along the ladder surface is still larger, but all of this is then corrected with the spatial map

For details: Hao Qiu HQiu@lbl.gov , Bob Connors RWConnors@lbl.gov
Full sector measurement takes ~ 8 hours

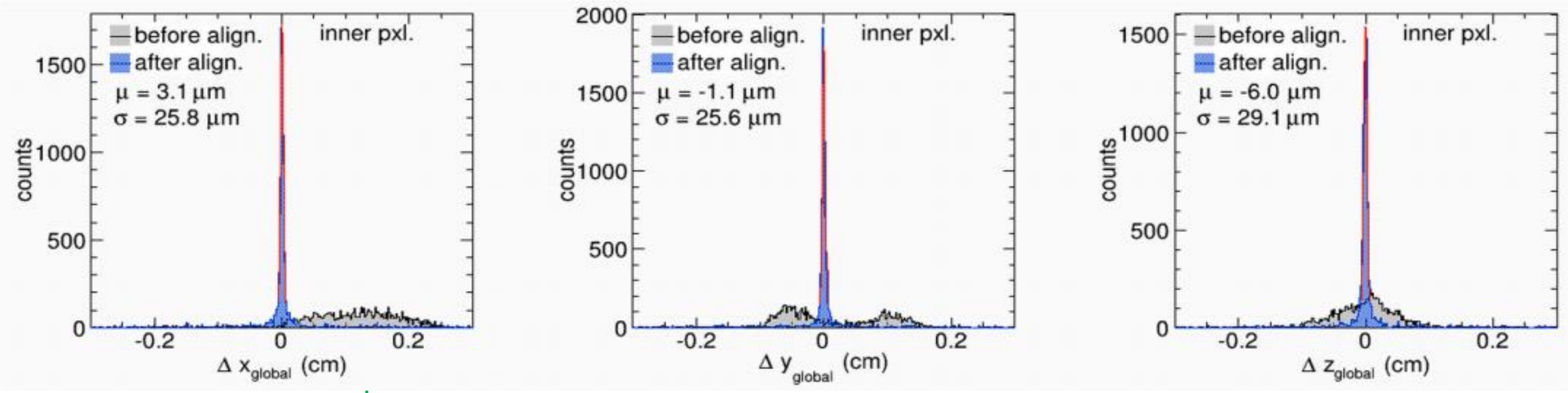
* Feather Probe, Optical Gaging Products (OGP), milligram level force, 1 mm ball
http://www.ogpnet.com/ogpAccFeatherProbe.jsp?page=41

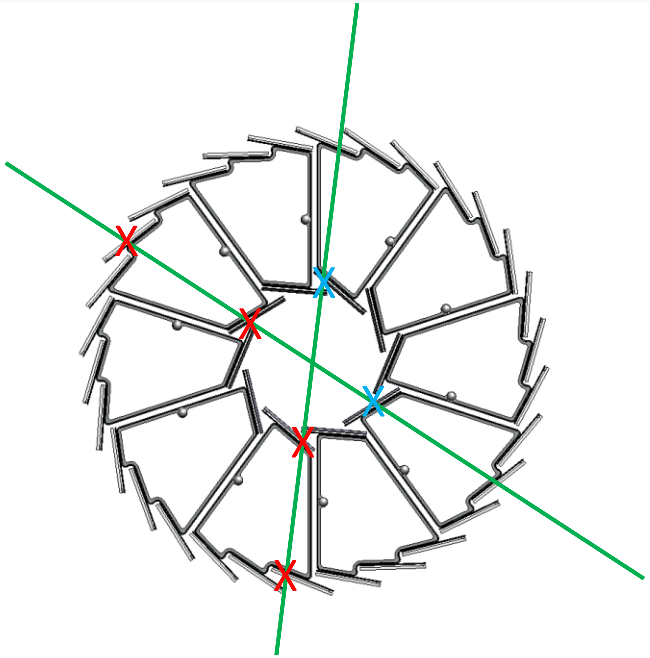


- After assembling sectors in a half shell sector tooling balls measured with touch probe relative to kinematic mount coordinate frame
- Since the shells are supported the same way in the CMM and in the STAR installation the relative pixel position mapping is not disturbed

duplicate, truncated PXL support tube with kinematic mounts

Final operating pointing performance in STAR





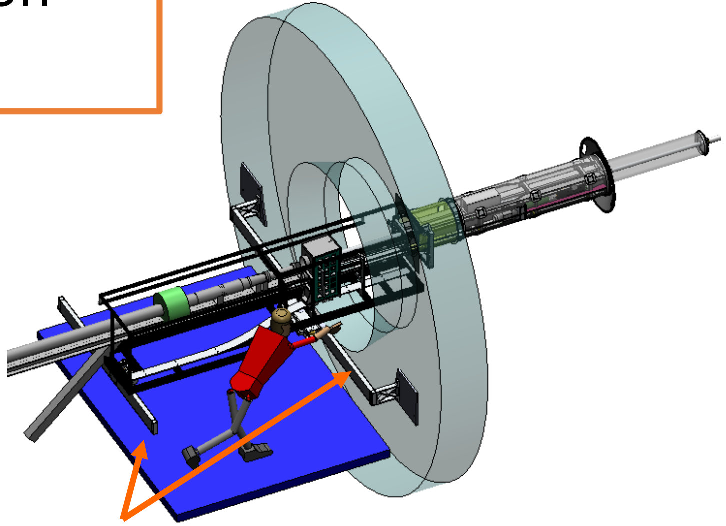
Cosmic ray result

Excellent half to half pointing, sub 30 μm

But after half to half alignment which was required to correct poor reproducibility of kinematic mount seating

Xs shows how hits are selected for projective distance of closest approach comparison

System for rapid PXL installation (external mechanics)

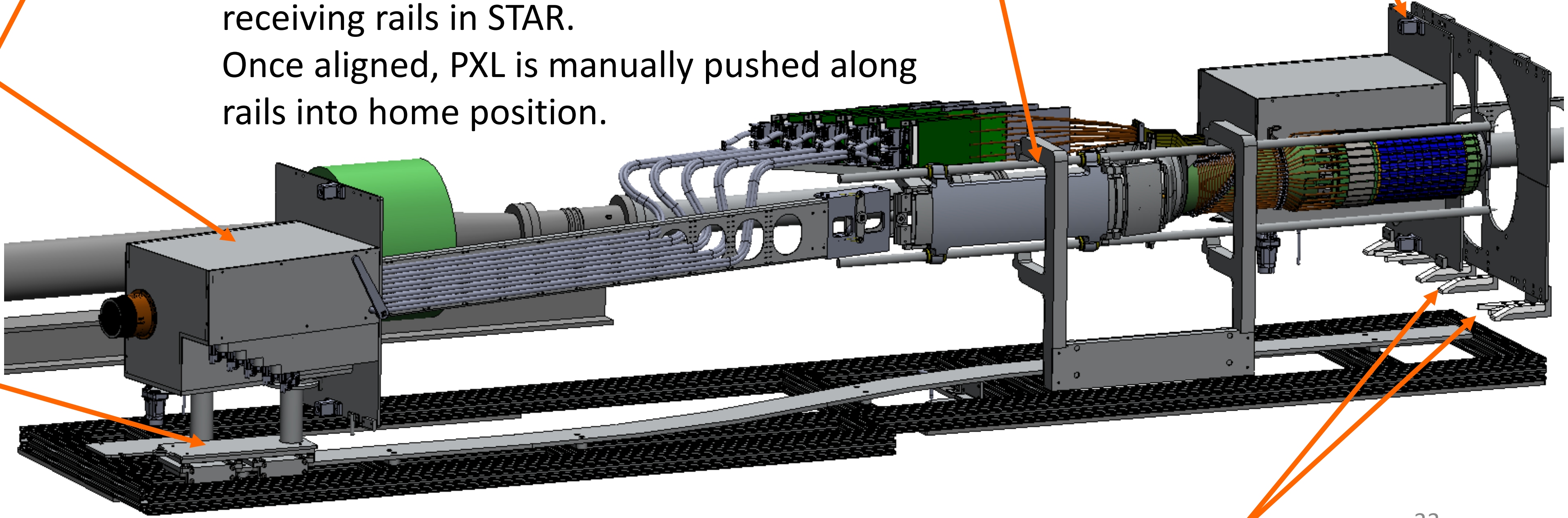


PXL carriage supported on slide rails in transport fixture

two captured screws, one top one bottom, secure and seal the bulkhead box to the detector housing

The 6 degree screw jack system, built into support, is used to align transport rails with receiving rails in STAR.
Once aligned, PXL is manually pushed along rails into home position.

Bulkhead box with all electrical and air connections

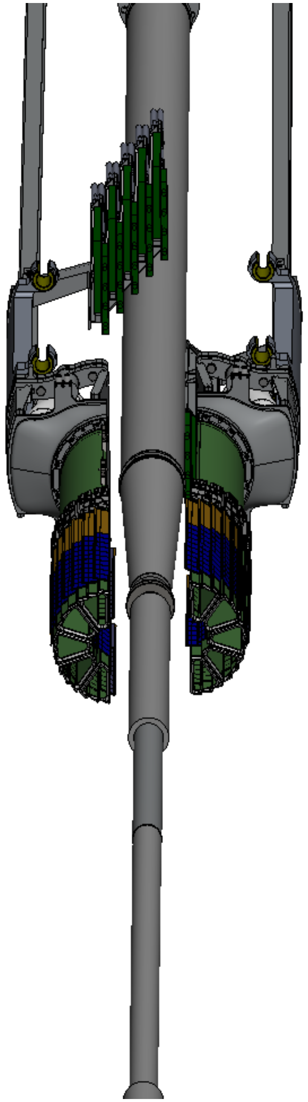


Trolley guide to steer box around beam pipe elements

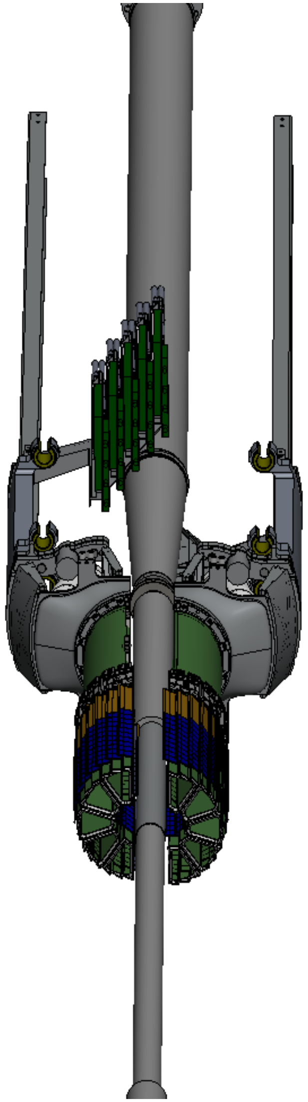
positioning guides to receive the bulkhead box

System for rapid PXL installation (internal mechanics)

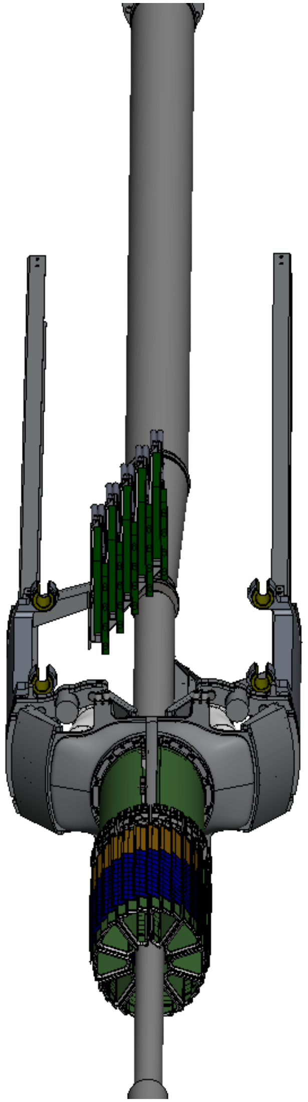
STAR HFT



open to clear beampipe flanges



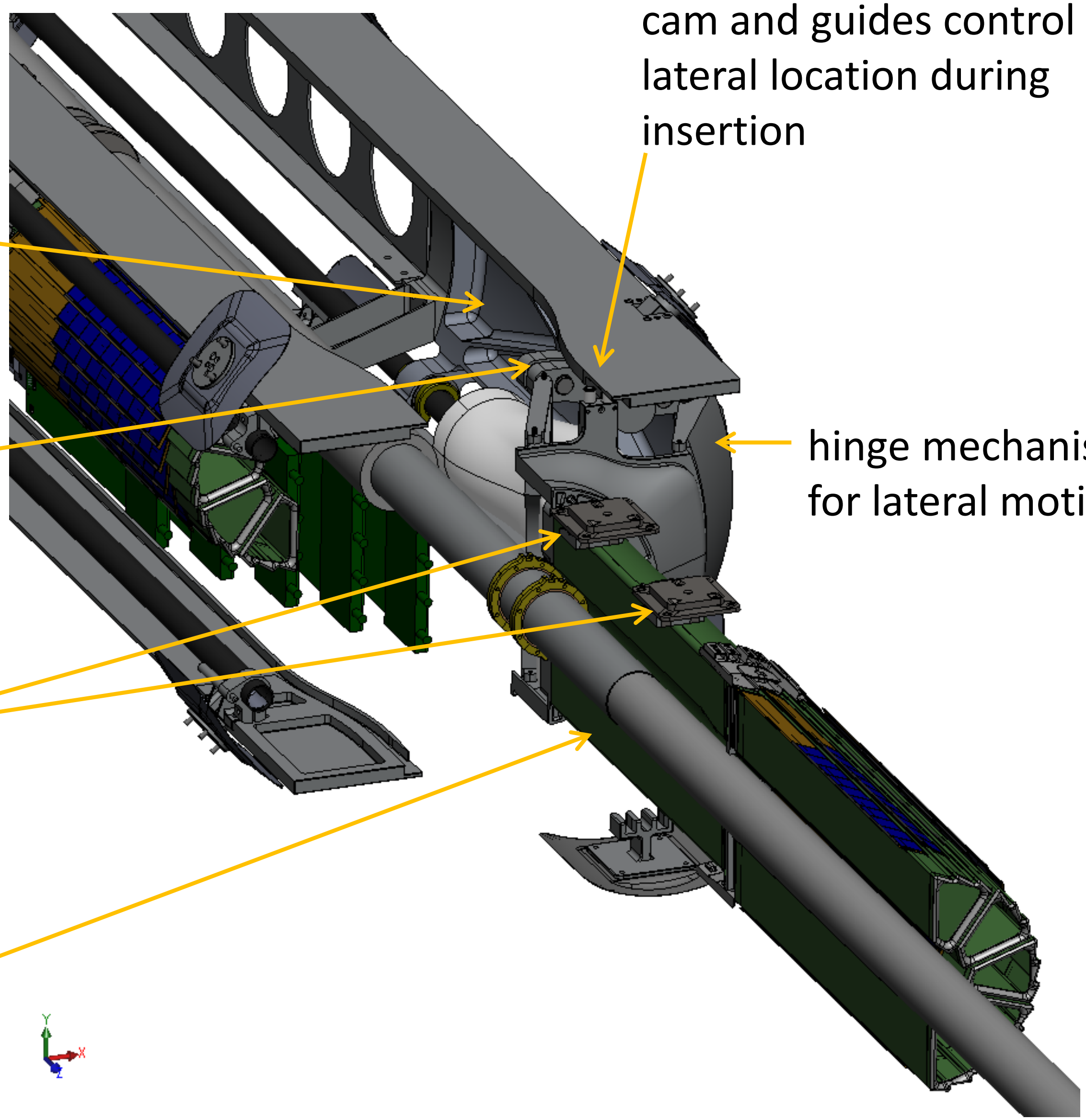
closing down



fully inserted and locked in kinematic mounts

As the PXL detector slides into home position it starts open to clear larger beam pipe sections. It then successively to closes down around the small beam pipe section and clears the narrowing outer containment tube.

System for rapid PXL installation (internal mechanics)



carriage rides on support rails

mechanical release to transfer load to kinematic mounts

kinematic mounts engage at home position

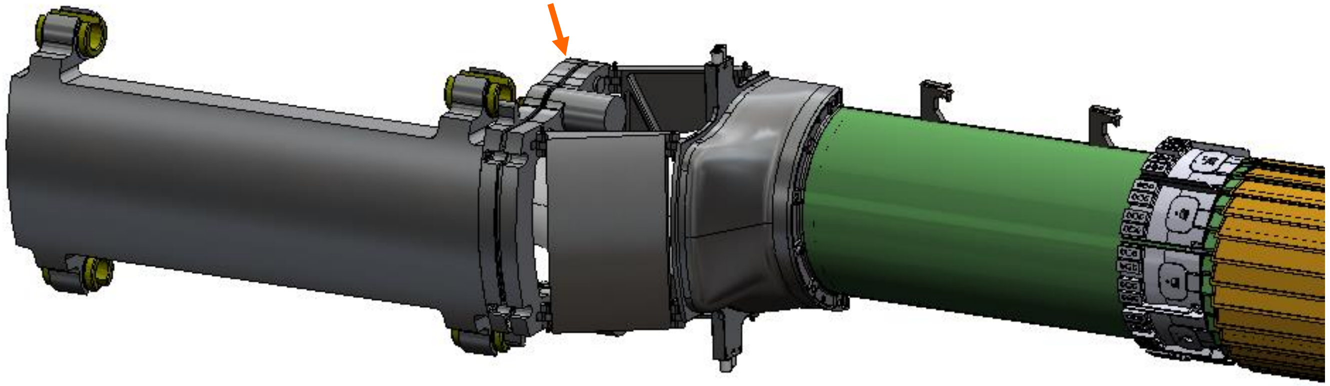
thin carbon half tube for PXL support and cooling air duct

cam and guides control lateral location during insertion

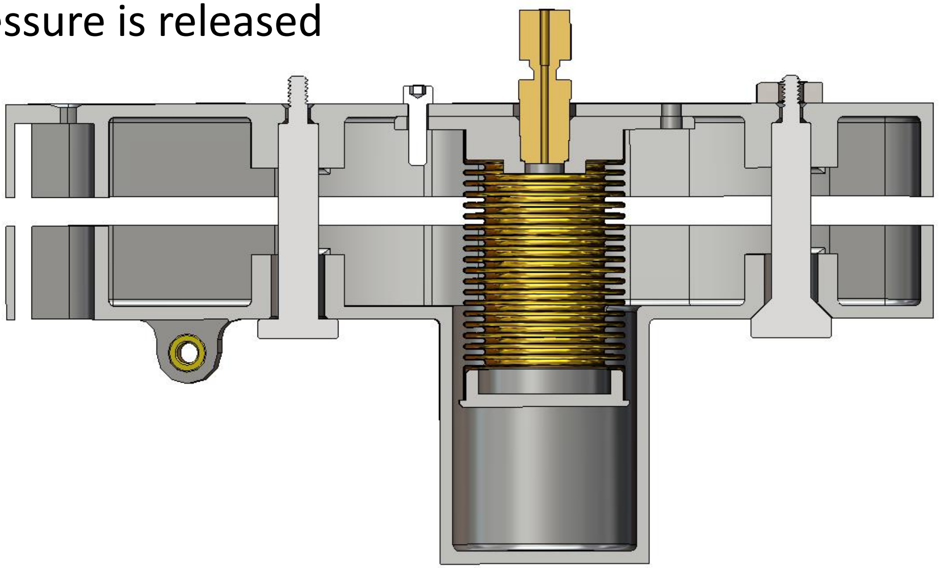
hinge mechanism for lateral motion

System for rapid PXL installation (internal mechanics)

Hold and release mechanism to transfer support from the rail carriage to the kinematic mounts



decouples carriage constraint when air pressure is released



cross section view

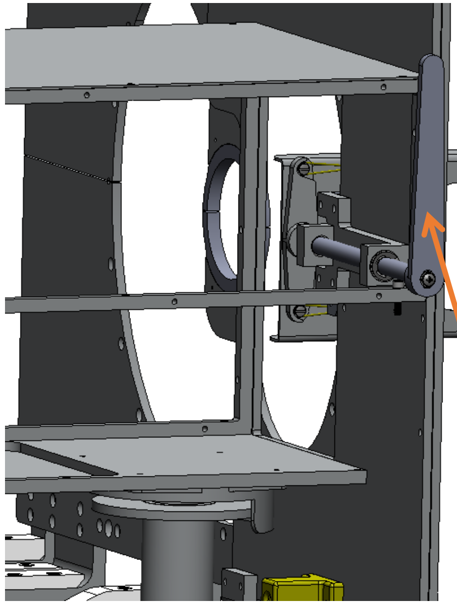
bellows piston locks coupling under pressure

By setting the correct air pressure this system also limits the engagement force applied to the kinematic mount

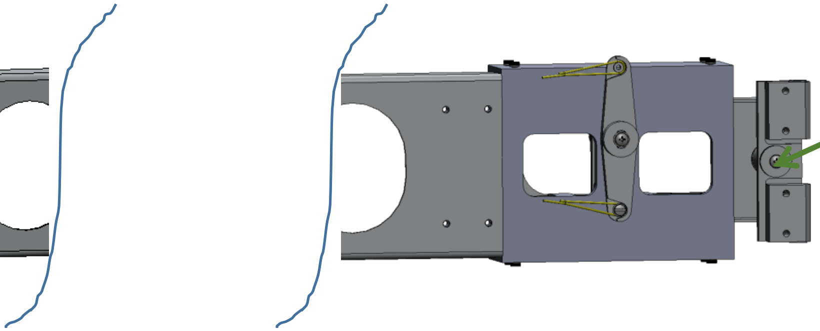
System for rapid PXL installation (internal mechanics)

STAR HFT

A lever actuated extender provides a reduced friction motion for the final engagement of the kinematic mounts. This allows better tactile feedback as the kinematic mount latches.



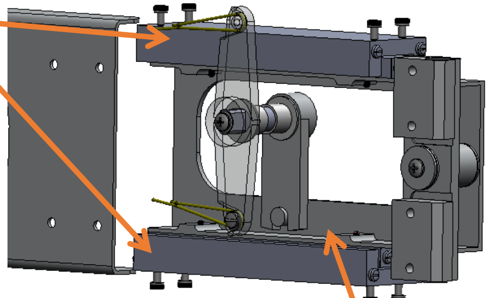
Extender mechanism



Pivot for vertical motion of the bulkhead box

Lever locate on the bulkhead box couples to extender with bronze cables.

Non magnetic linear bearings



Cam driven slide

HFT PXL detector

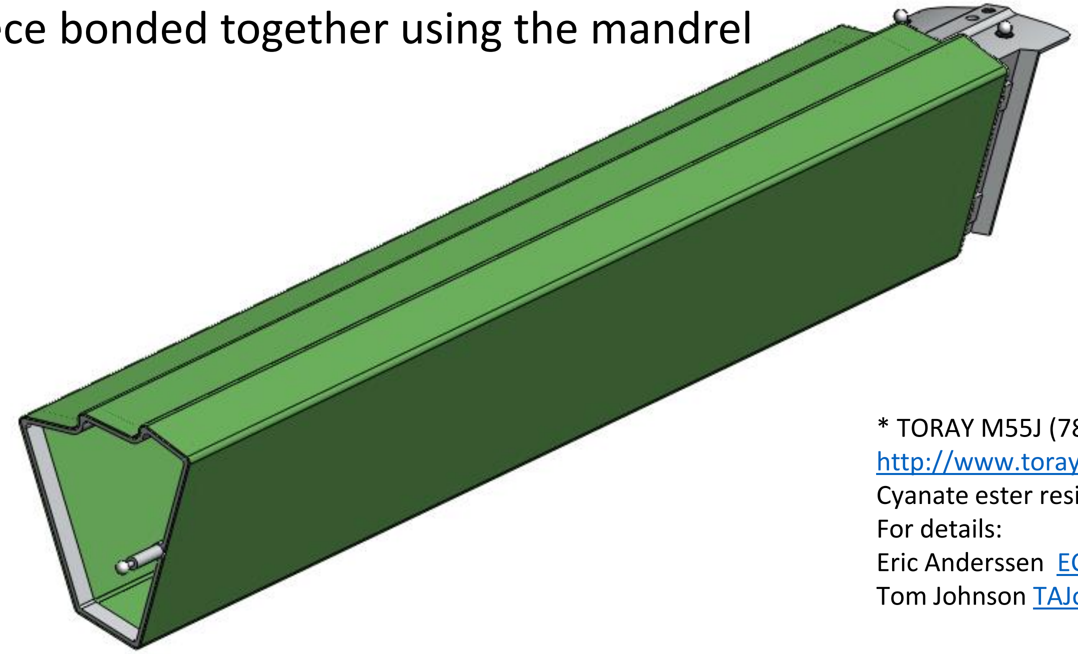
First MAPS based vertex detector installed and operating in STAR

end

Fabrication details

Stiff Carbon Composite Sector Tube, large moment of inertia

- 260 μm thick wall
- unidirectional carbon fiber with cyanate ester resins*
- 7 layer, 0,-60,+60,0,+60,-60,0 deg layup for reduced cure warpage
- Layup in two halves on an aluminum mandrel with caul plate control of inside radius features
- vacuum bagged and Autoclave cured
- 2 piece bonded together using the mandrel



* TORAY M55J (78 Msi/538 Gpa) PAN GRAPHITE/EX-1515
http://www.toraycompam.com/
Cyanate ester resin system, TenCate EX-1515 http://www.tencate.com/amer/Images/EX1515_DS_Web_05121429-3894.pdf
For details:
Eric Anderssen ECAnderssen@lbl.gov
Tom Johnson TAJohnson@lbl.gov

ladder assembly fixture

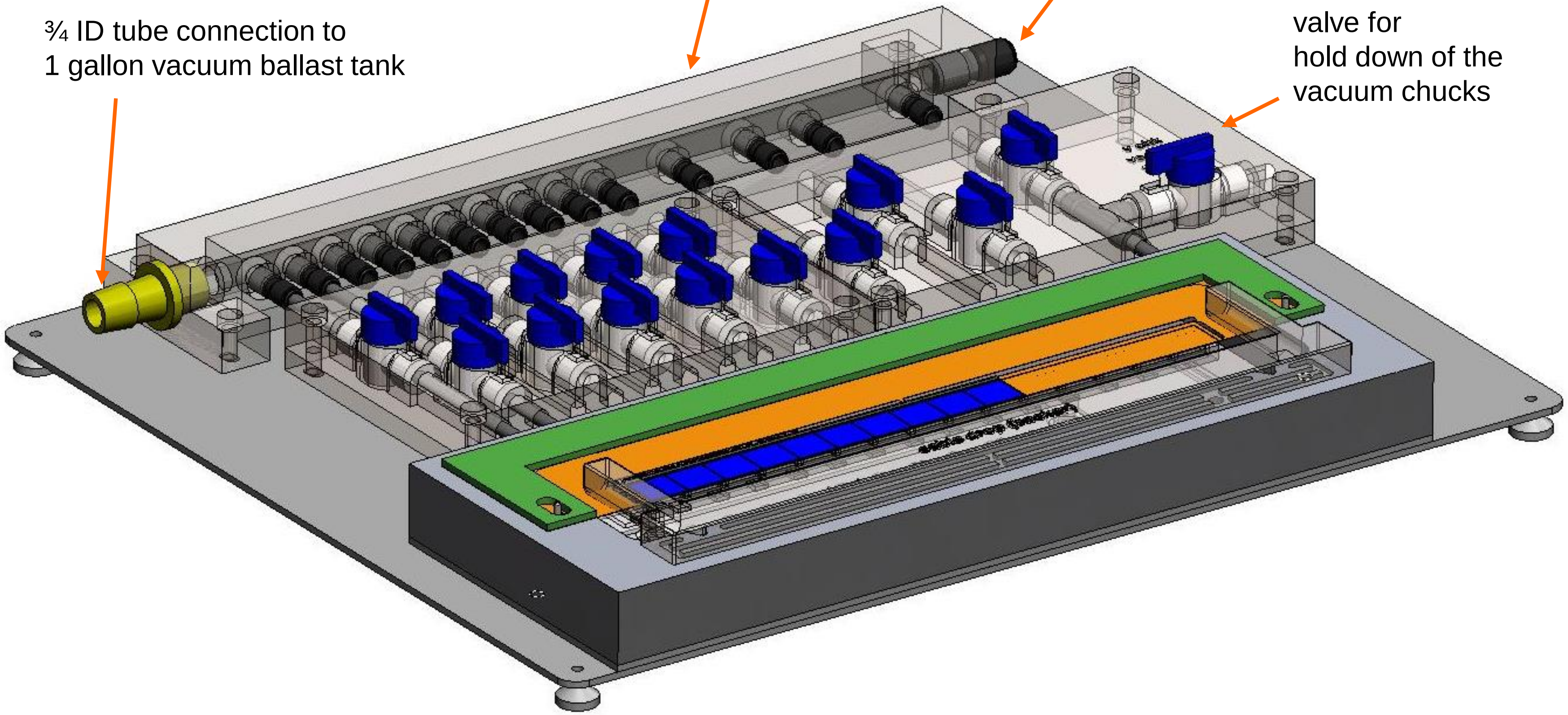
vacuum chuck system for placing chips and other ladder parts

3/8 OD tube connection to vacuum

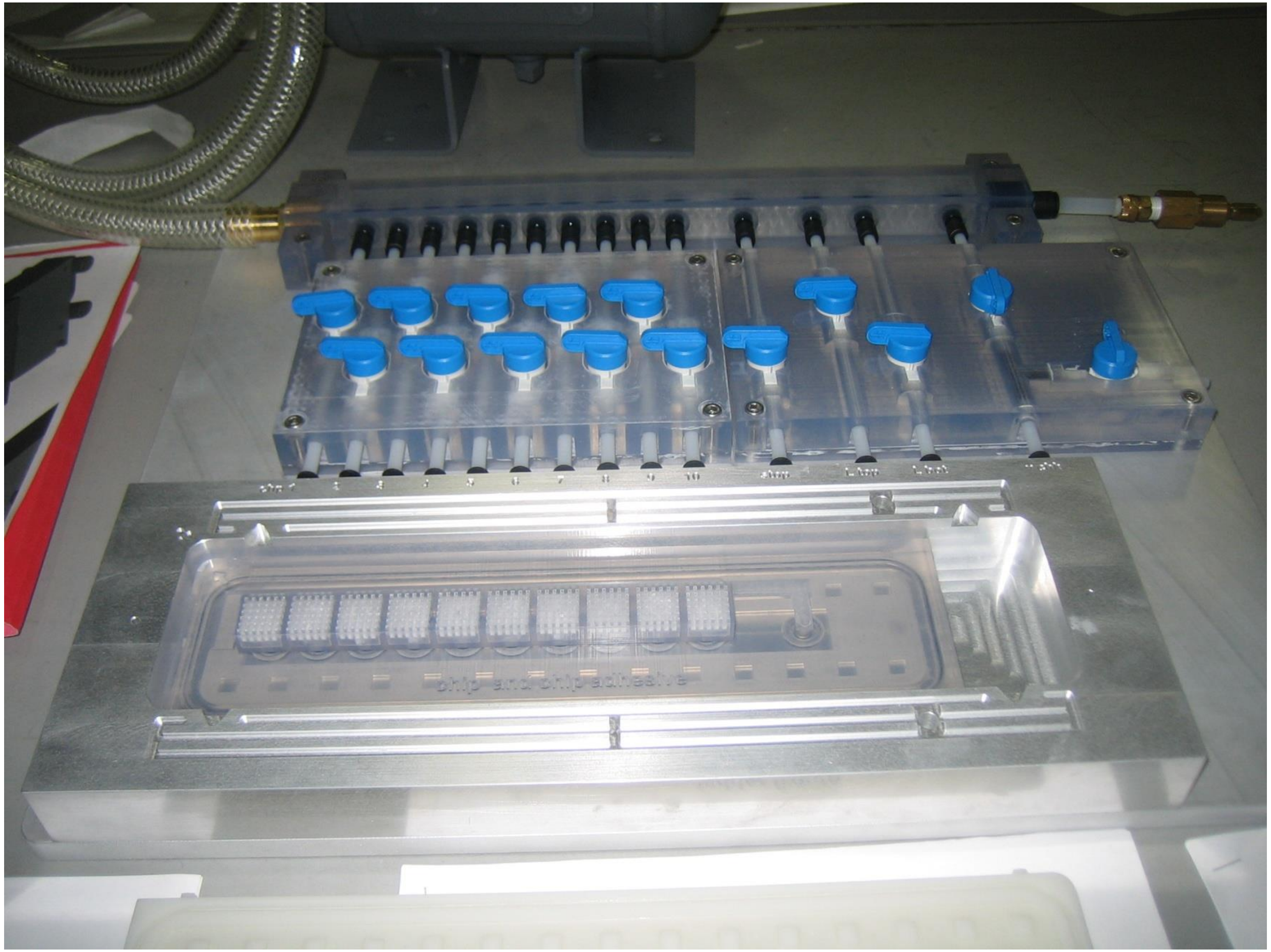
vacuum distribution manifold

vacuum release valve for hold down of the vacuum chucks

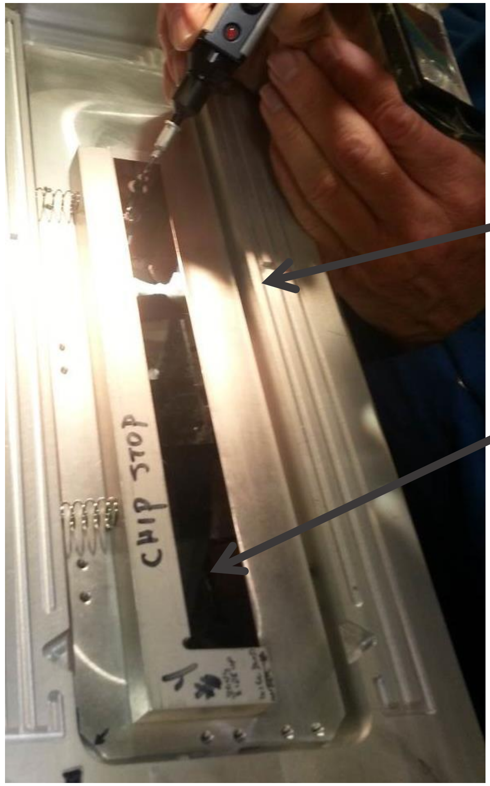
¾ ID tube connection to 1 gallon vacuum ballast tank



Ladder assembly fixture



PXL Ladder Assembly



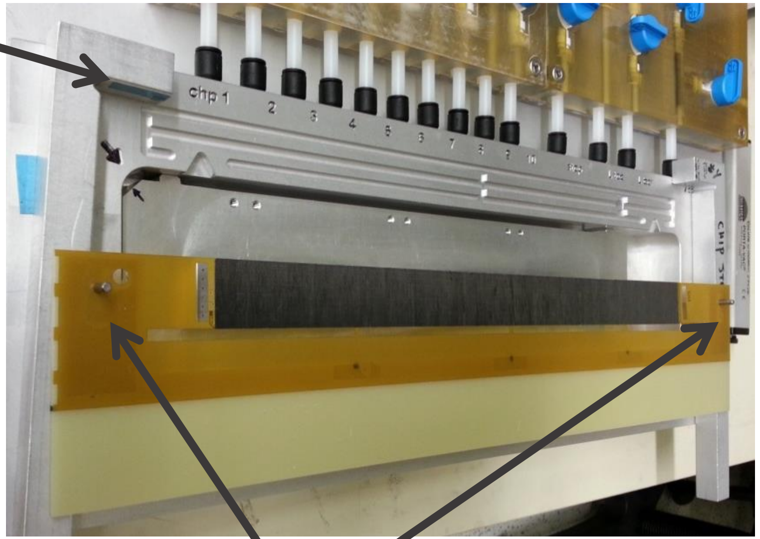
Sensor positioning

Precision vacuum chuck fixtures to position sensors by hand.

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

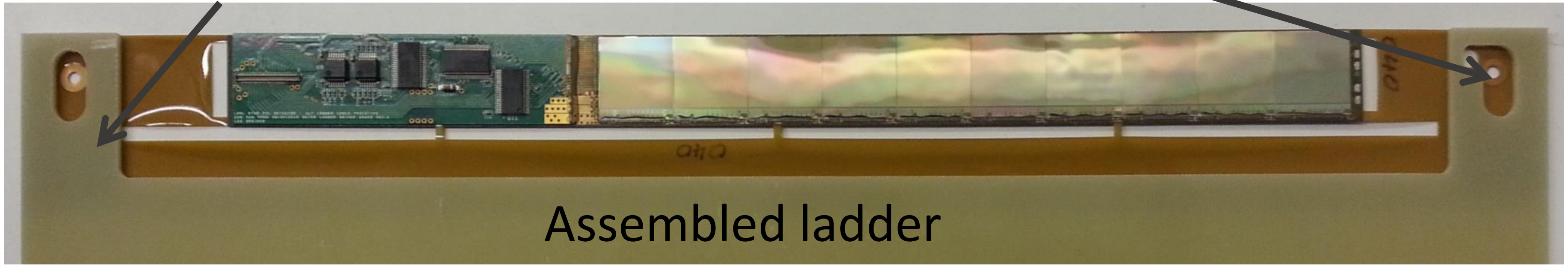
Weights taken at all assembly steps to track material and as QA.

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



Cable reference holes for assembly

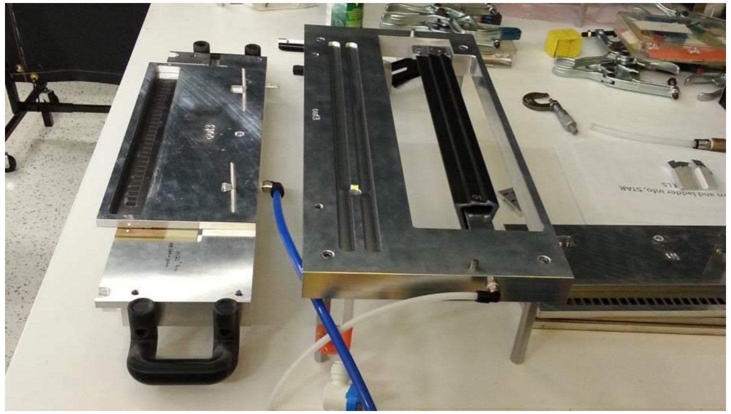
FR-4 Handler



Assembled ladder

Sector and detector half assembly

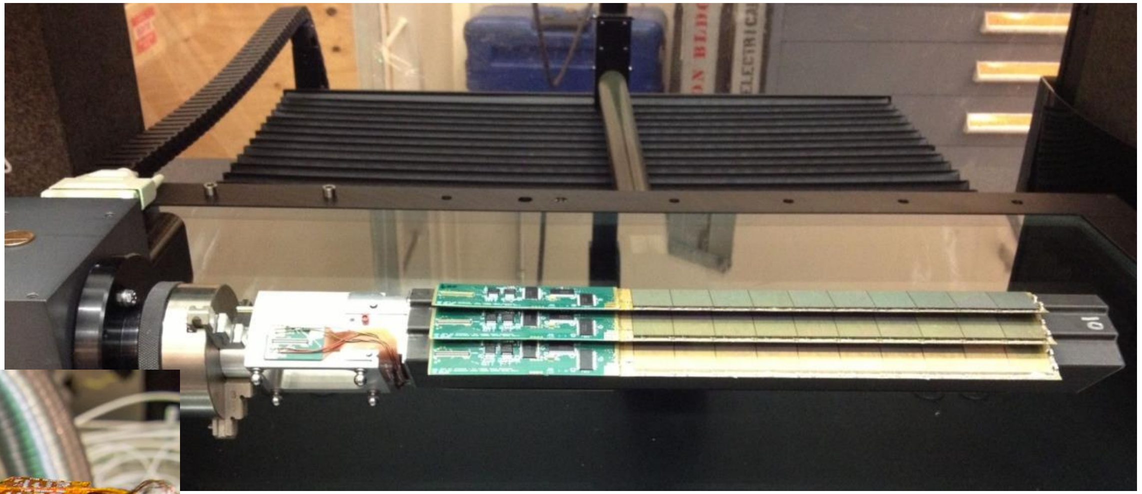
STAR HFT



Sector assembly fixture

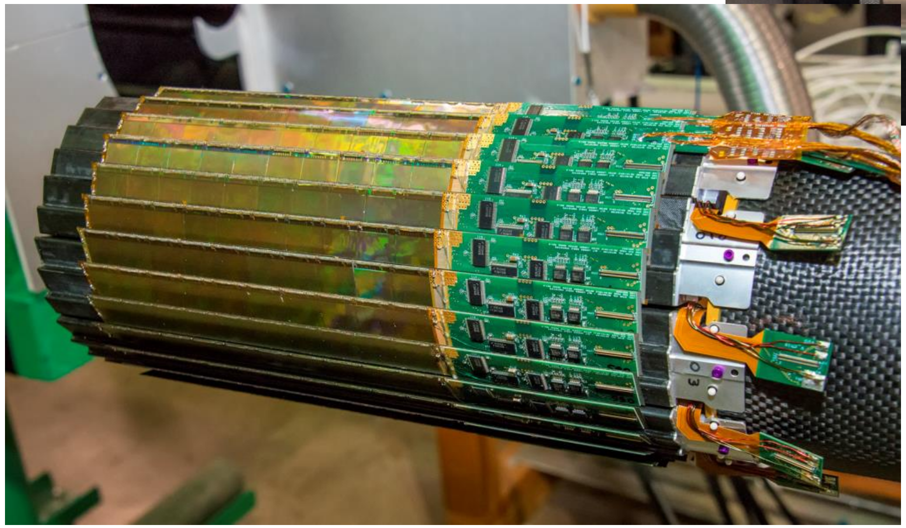
Sectors

- 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

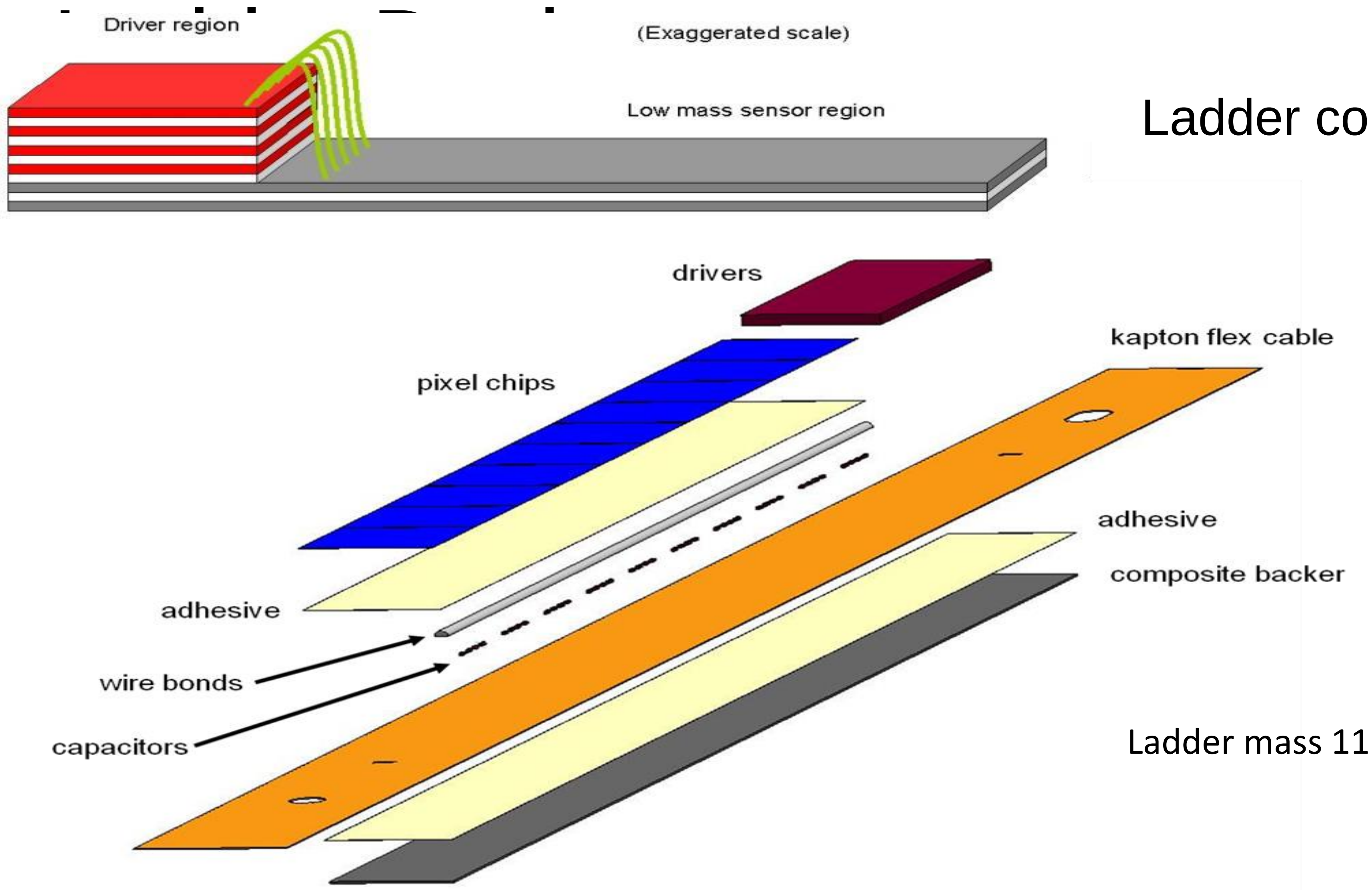
A detector half



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

extra material

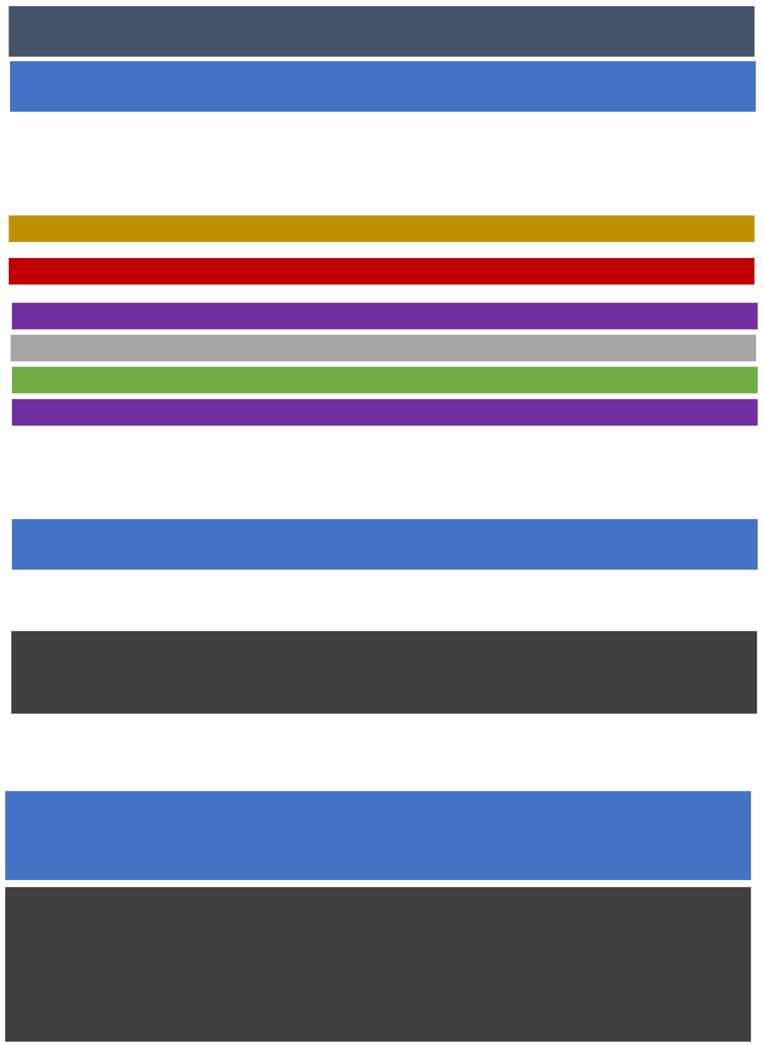


Ladder construction

Ladder mass 11.6 grams

Soft sheet adhesive
3M 467MP 200MP adhesive, acrylic 2 mil sheet, shear modulus 1.5×10^4 Pa (2 psi)

Radiation length in low mass area



Si 50um (0.0529%)
acrylic 50um (0.0148%)
→ 0.0677%

Encapsulant + bond wires (0.070%)
Capacitors + solder (0.0035%)
Coverlay (0.0075%)
Al 30um – both sides (0.0248%)
kapton 50um (0.0148%)
Coverlay (0.0075%)
→ 0.128%

acrylic 50um (0.0148%)
Carbon composite 125um (0.0293%)
→ 0.0441%

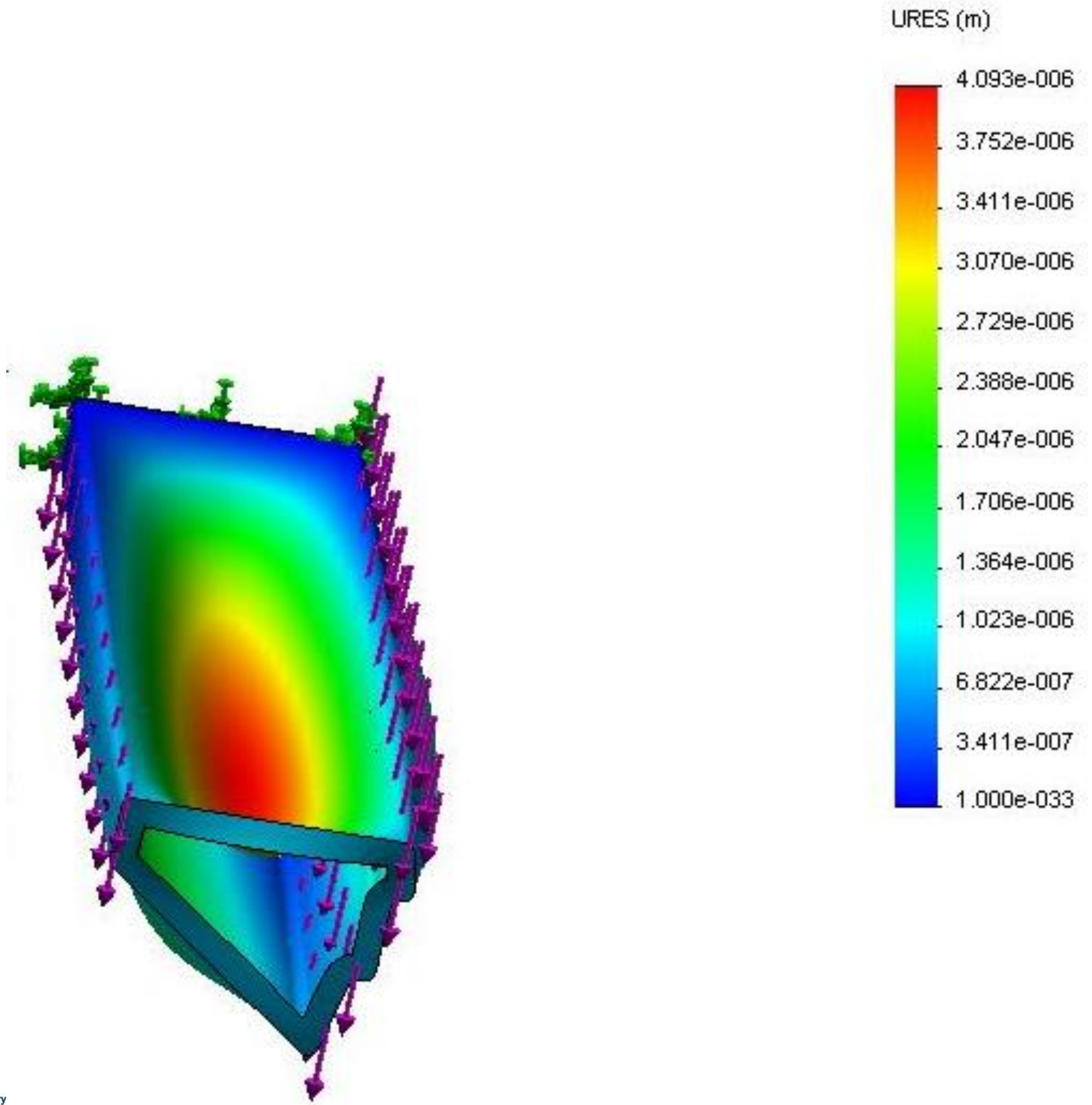
Si adhesive 100 um (0.0469%)
Carbon composite 250um (0.1017%)
→ 0.1486%

from older estimate

Total = 0.388%

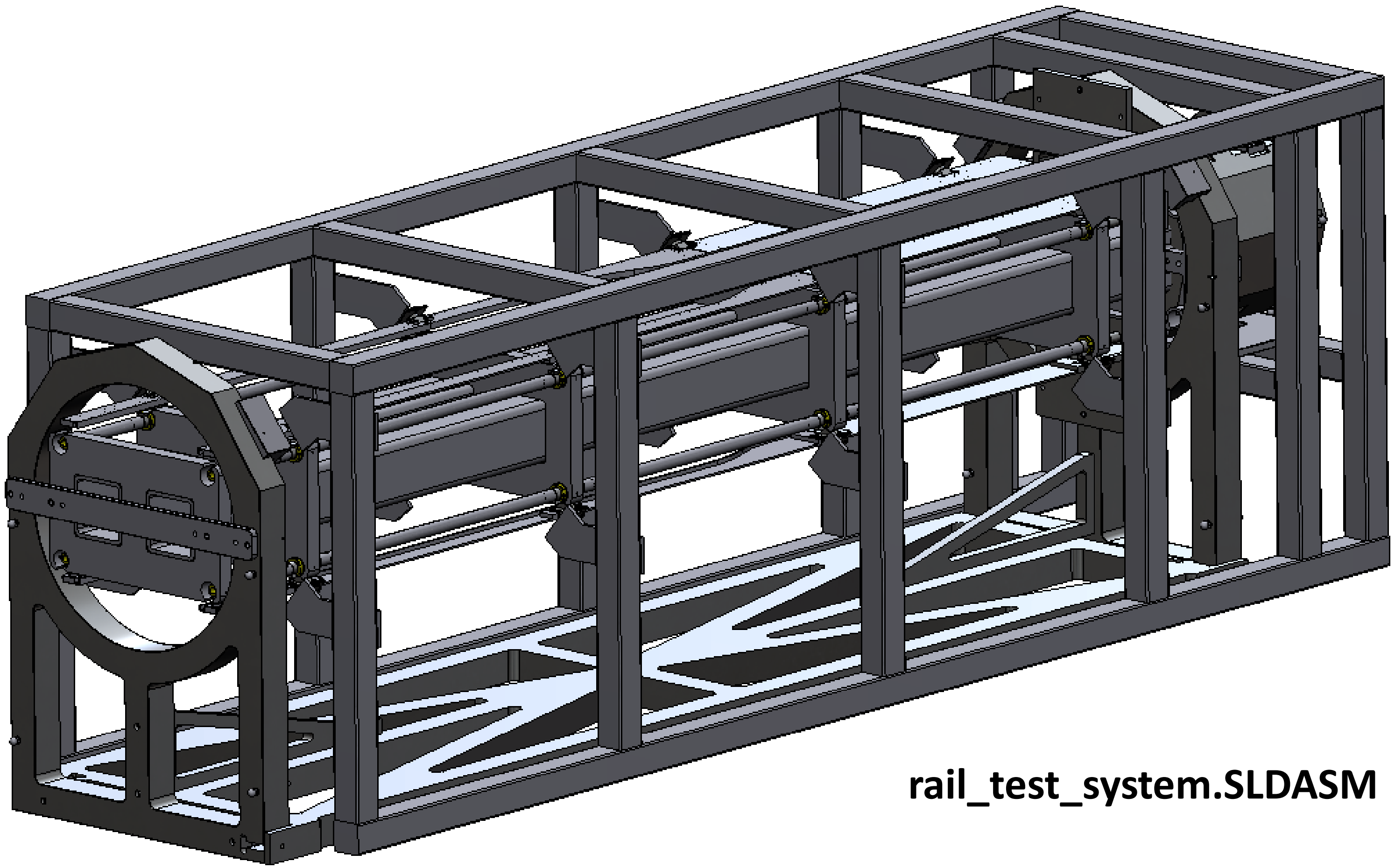
NOTE: Does not include sector tube side walls

FEA analysis - sector beam deformation – gravity load



- FEA shell analysis
- 120 micron wall thickness composite beam
- gravity load includes ladders
- maximum structure deformation 4 microns
- ladder deformation only 0.6 microns

rail test system

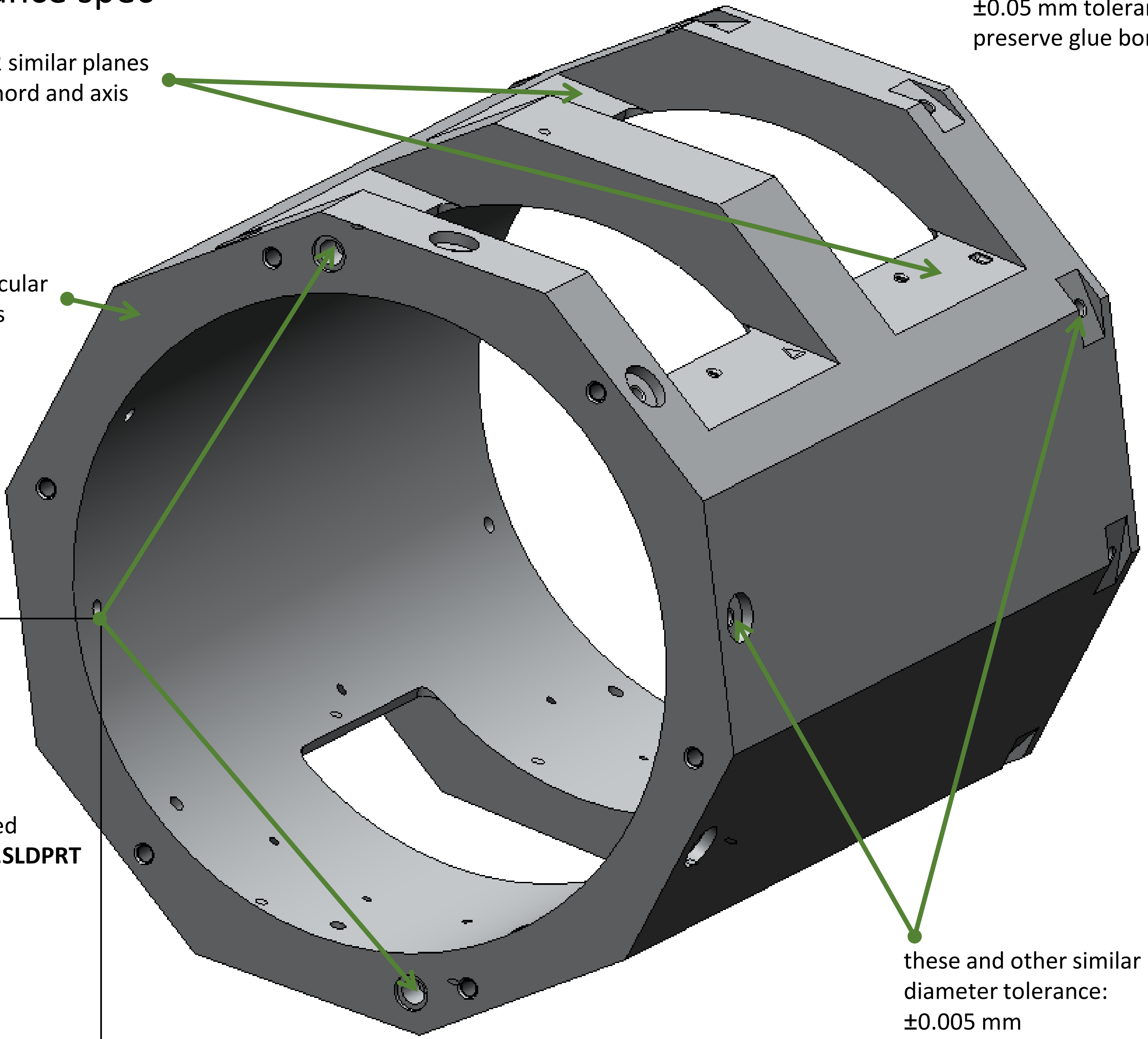


rail_test_system.SLDASM

5/3/2010
this document: http://www-rnc.lbl.gov/~wieman/Rail_test_system.pptx
models: http://www-rnc.lbl.gov/~wieman/rail_test_system_05_03_10.zip

Example tolerance spec

±0.05 mm tolerances are to preserve glue bond thicknesses



this and other 2 similar planes tolerances to chord and axis of ref cylinder: ±0.05 mm

this plane perpendicular to a ref cylinder axis

line between holes centered on ref cylinder axis to ±0.05 mm

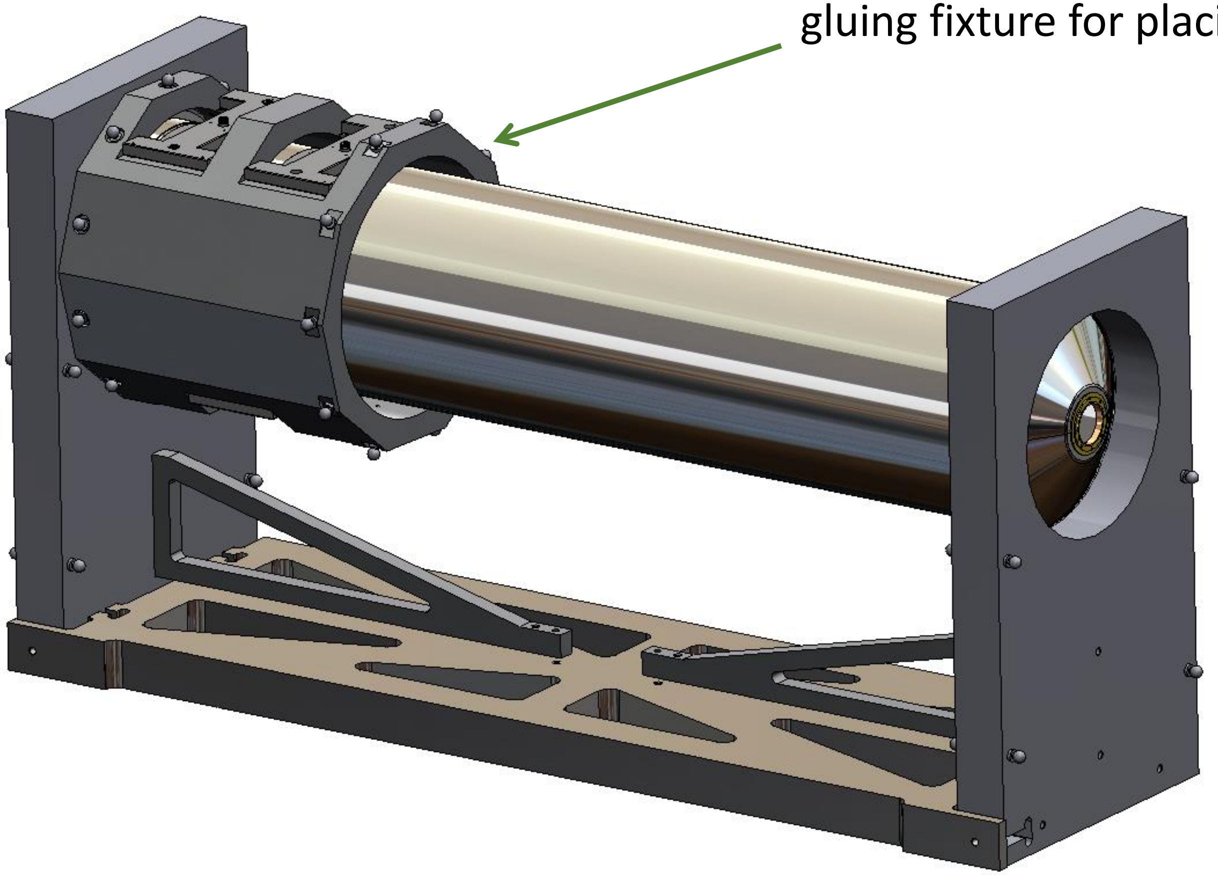
separation tolerance ±0.05 mm or match drilled with **butch_plate_single.SLDPRT**

diameter tolerance:
+0.000 mm
-0.005 mm
for bullet insert press fit

these and other similar holes diameter tolerance:
±0.005 mm
for press fit with tooling balls, glue in OK if ends up sloppy

grand_master.SLDPRT

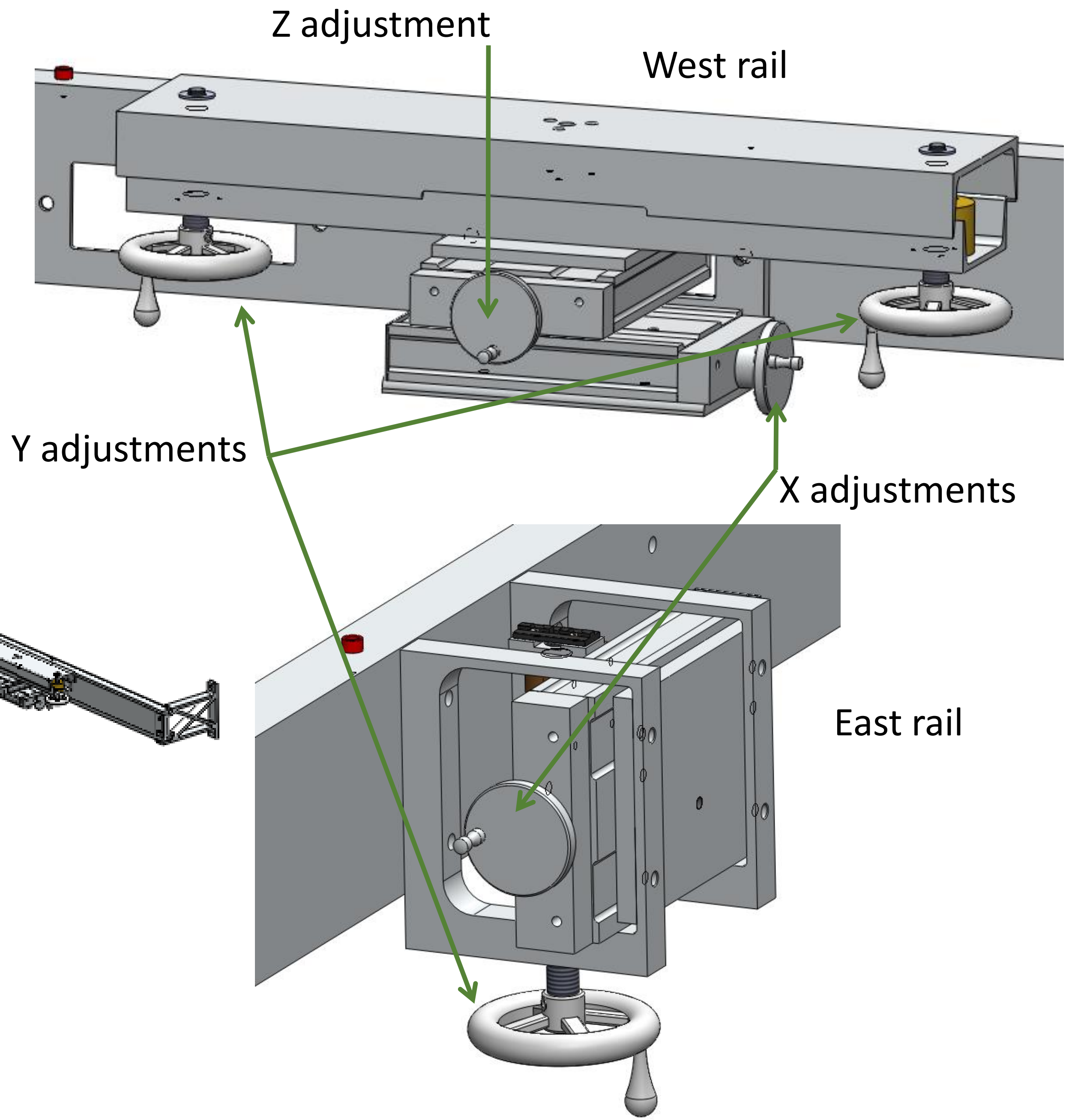
gluing fixture for placing kinematic mounts in PST

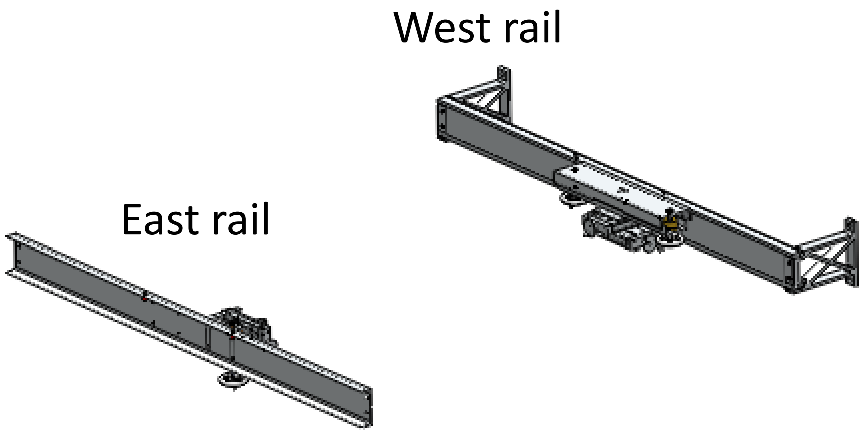


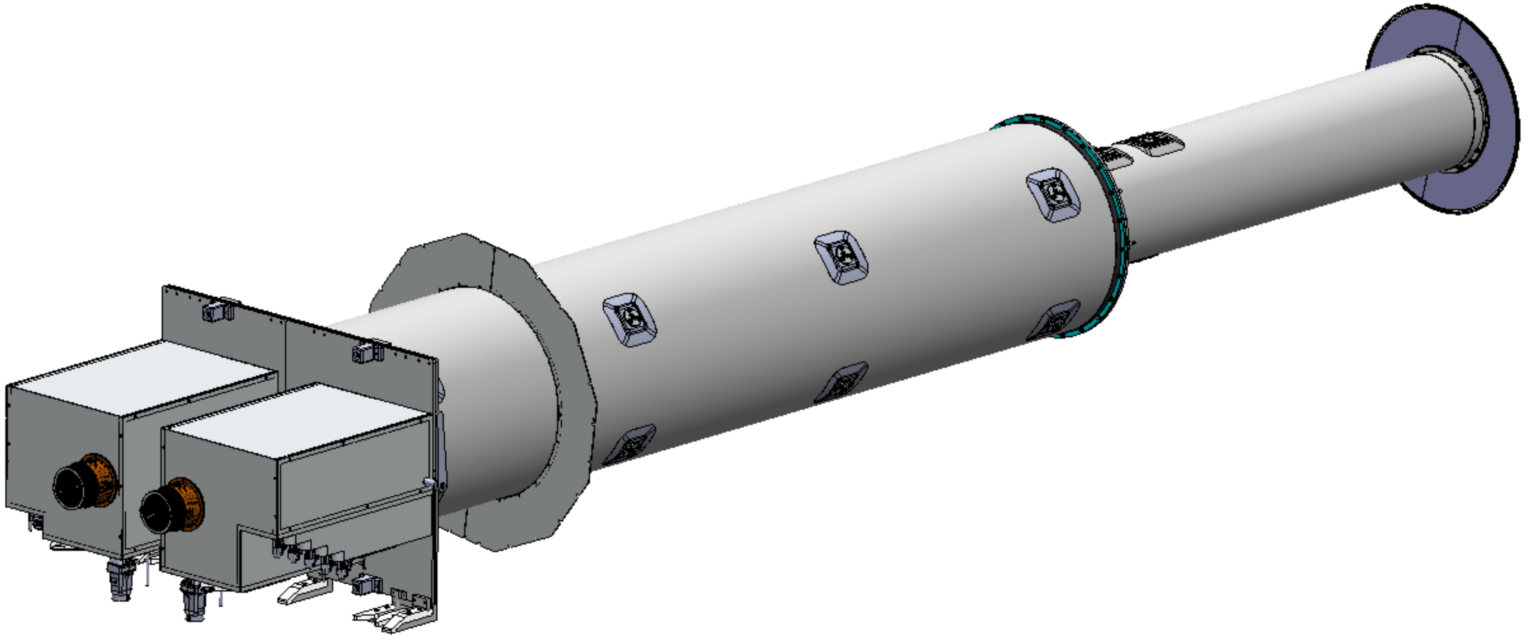
Fine adjustment system

Full 6 degrees of adjustment

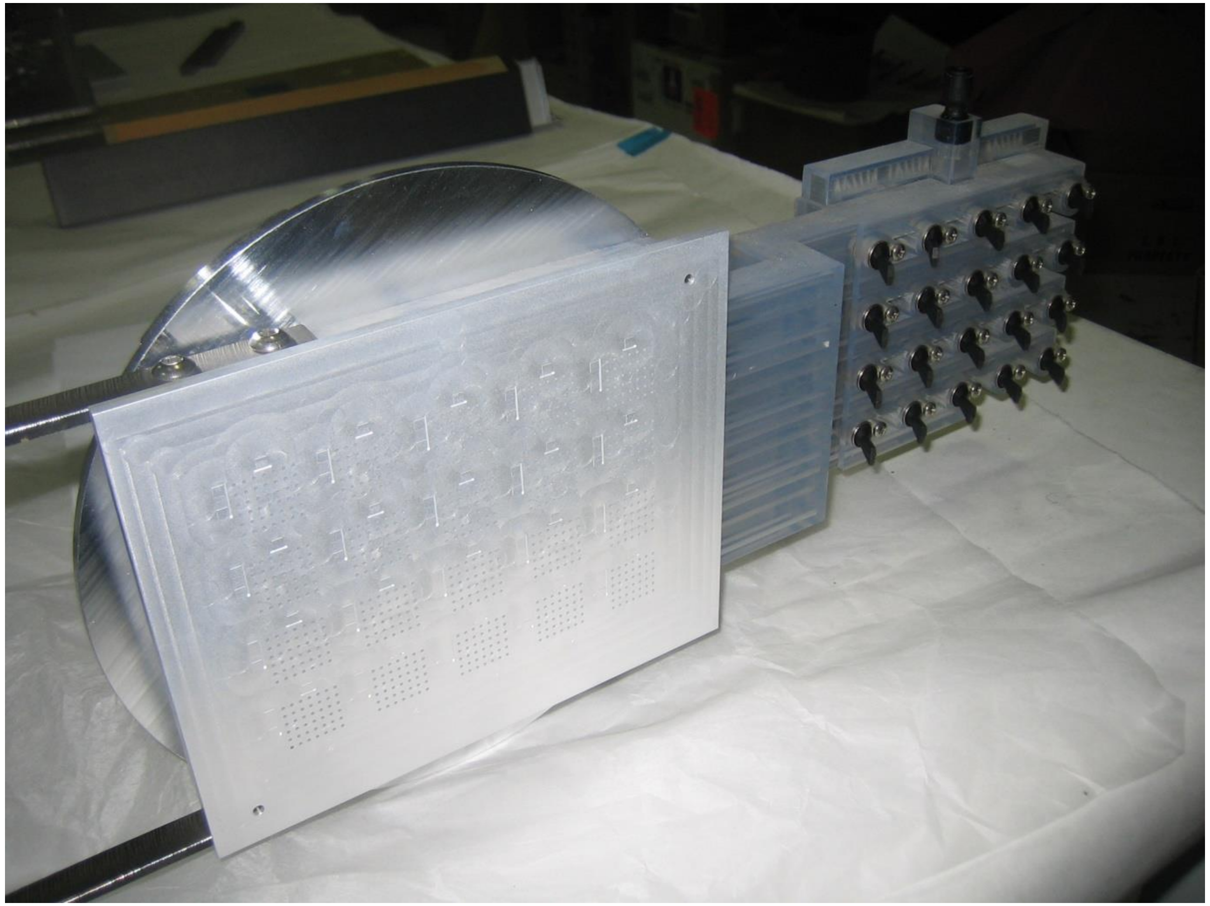
Adjustment range > ± ½ inch







vacuum chuck for thinned silicon chips in the probe station.
plumbing done with rapid prototyping and cartridge valves



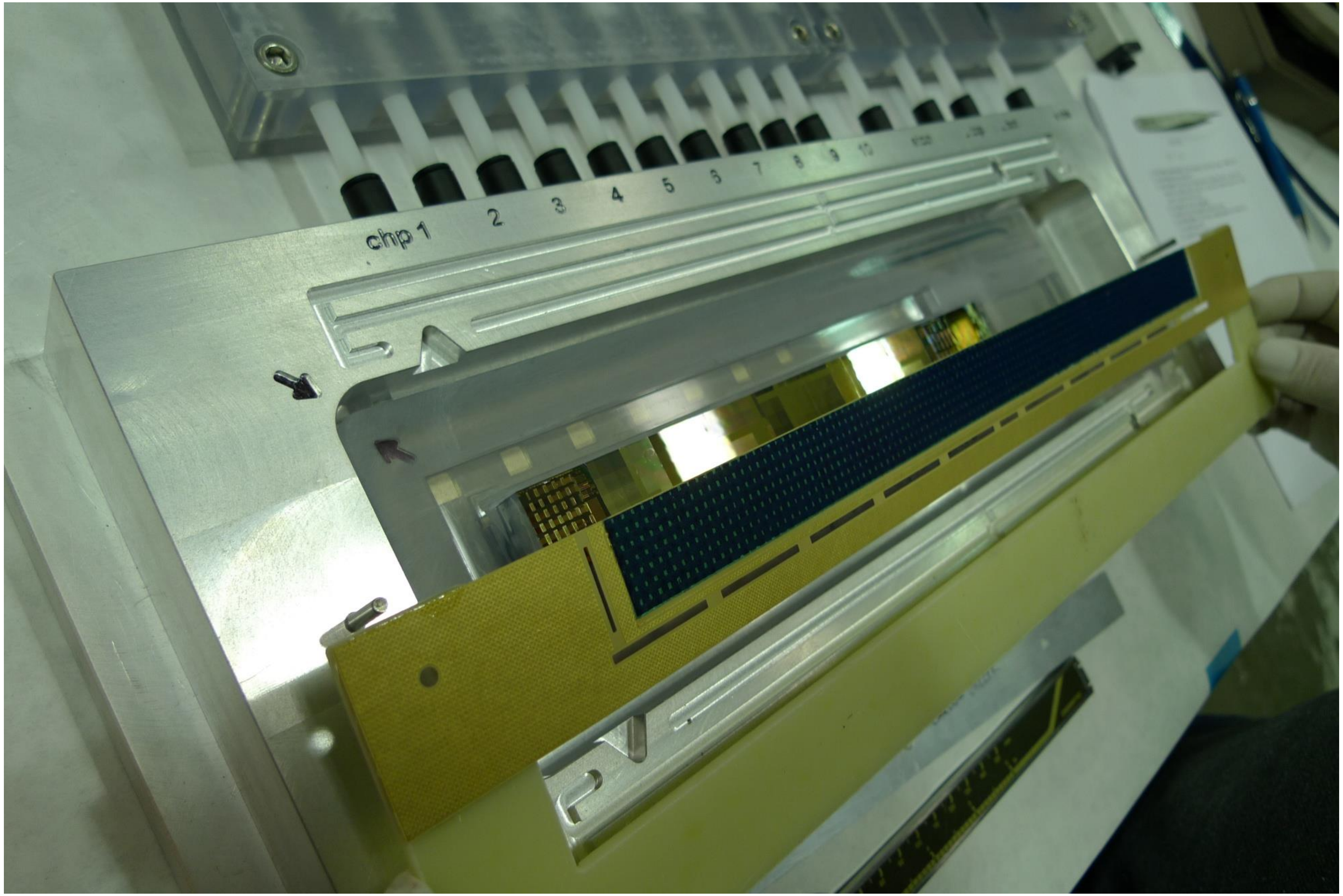
ladder fabrication and tooling

STAR HFT

Lawrence Berkeley National Laboratory

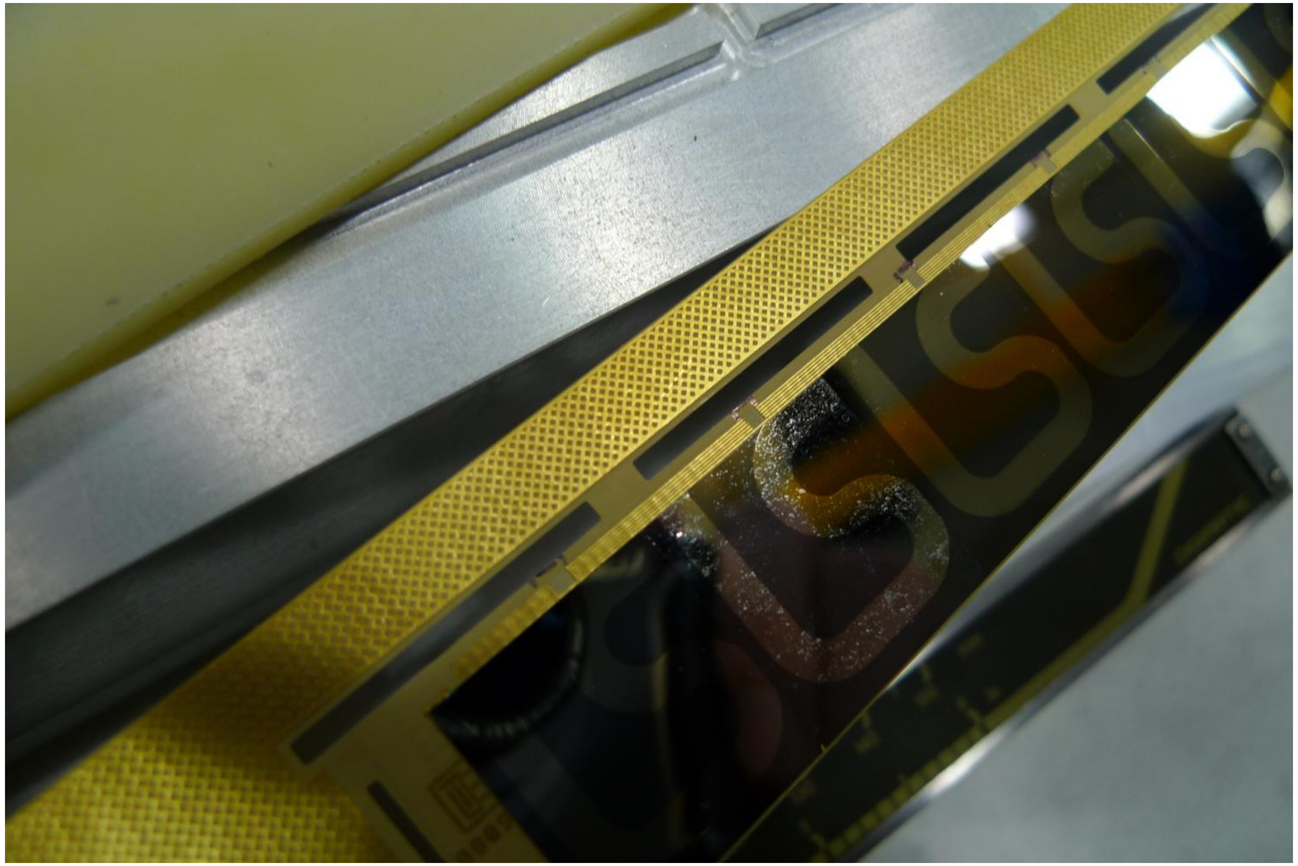
ladder fabrication and tooling

ladder fabrication and tooling



finalizing mechanical designs and developing rapid production methods

ladder fabrication and tooling

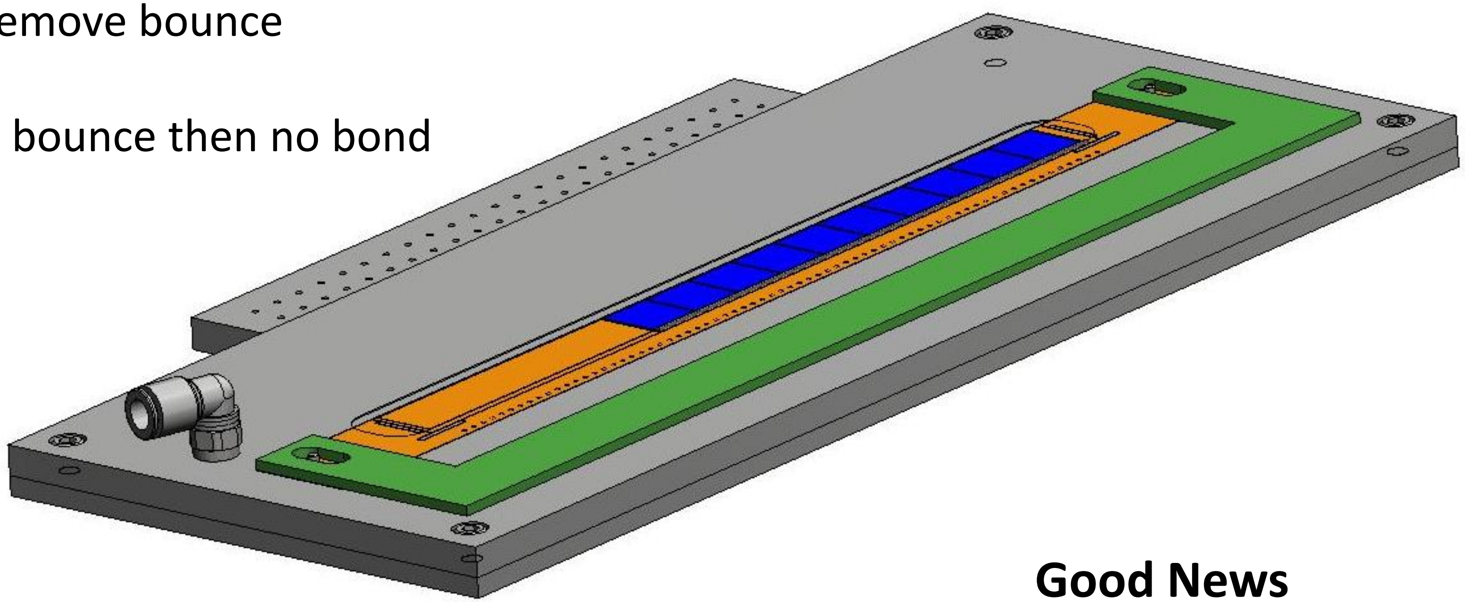


ladder with
silicon heater
chips
(50 μm thick)

wire bonding 50 μm silicon to flex PC

vacuum chuck to
secure flex and silicon
flat against solid surface
to remove bounce

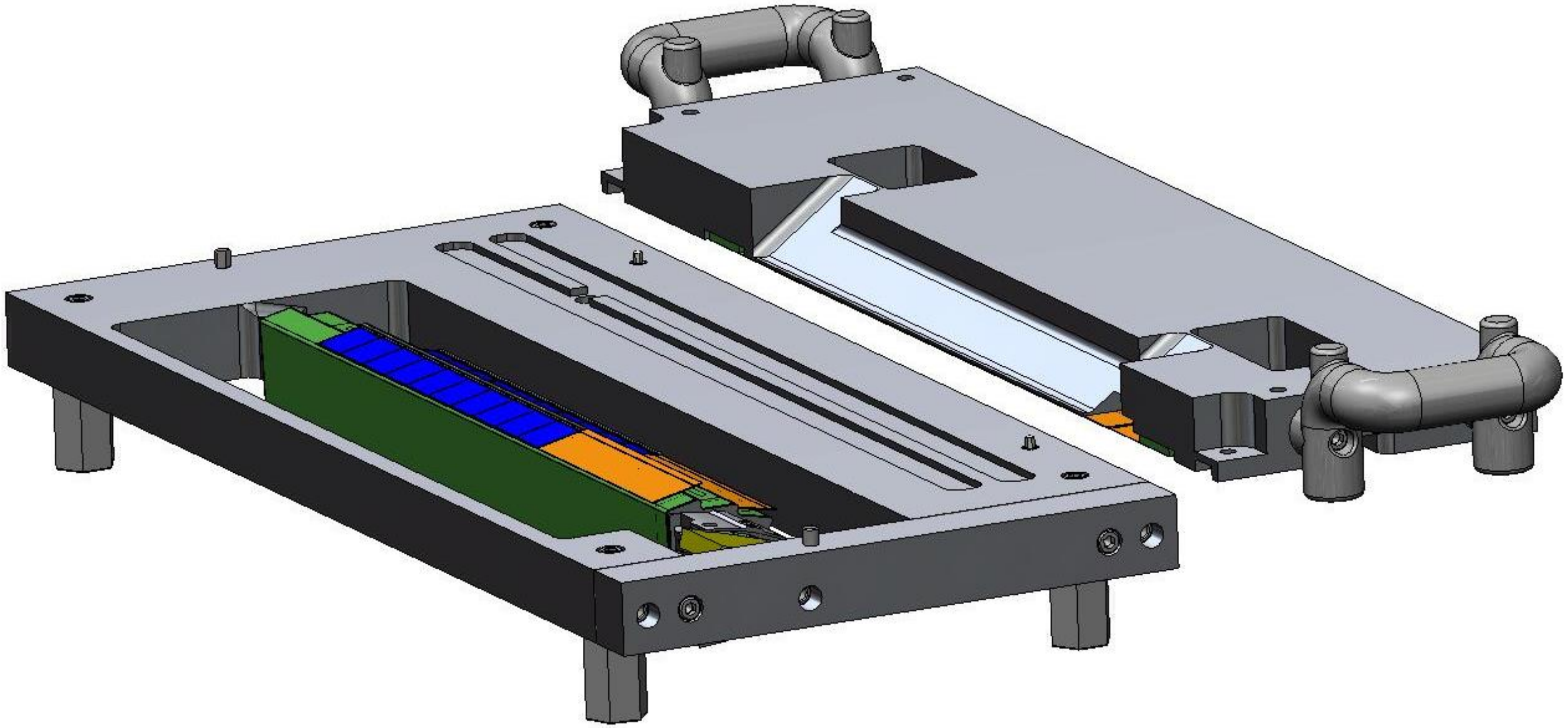
Any bounce then no bond



Good News
after a couple of minor
modifications to the vacuum
chuck wire bonding works well

fixture

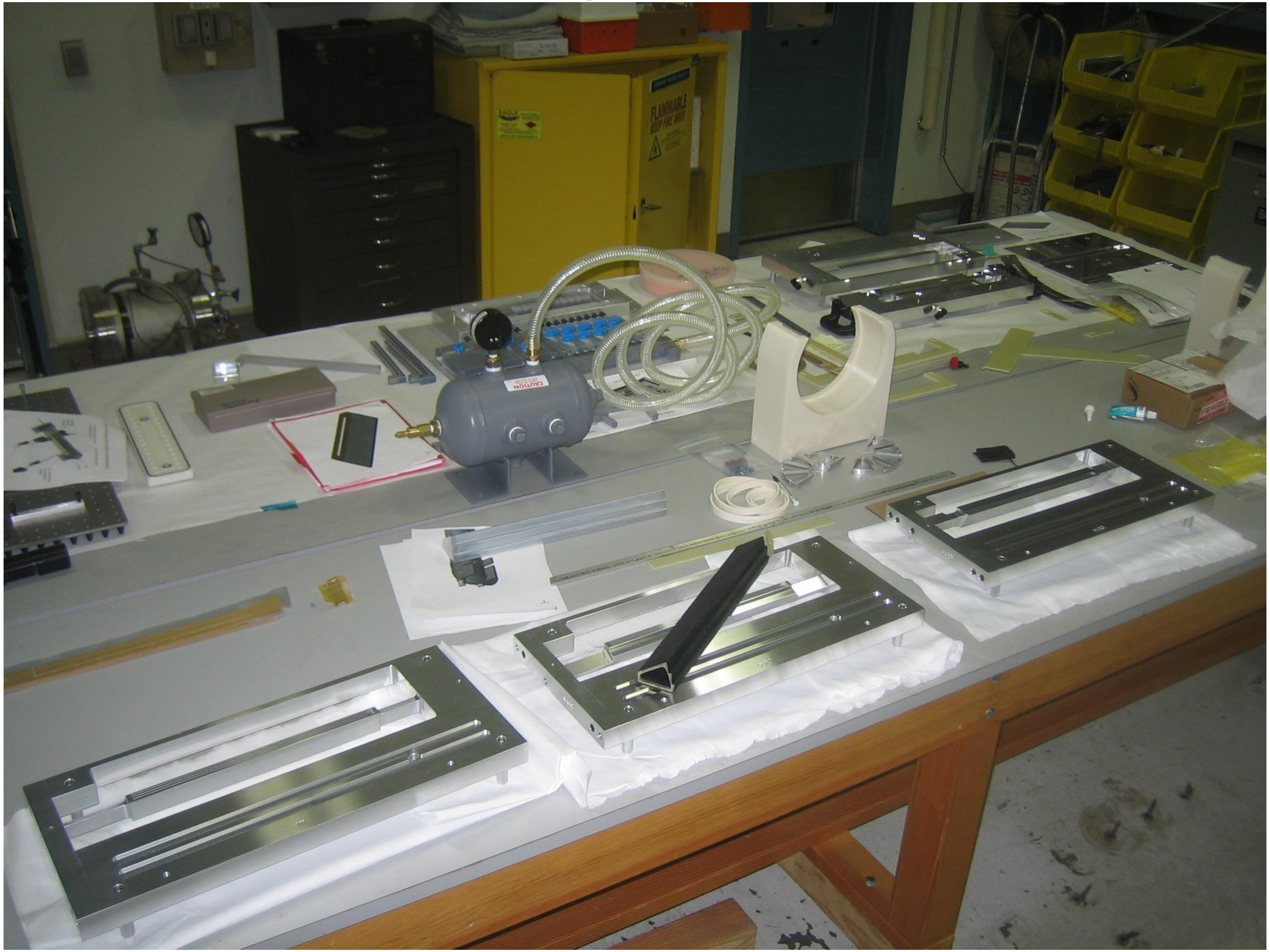
(designed to allow ladder replacement)



ladder to out2 bond fixture.SLDASM

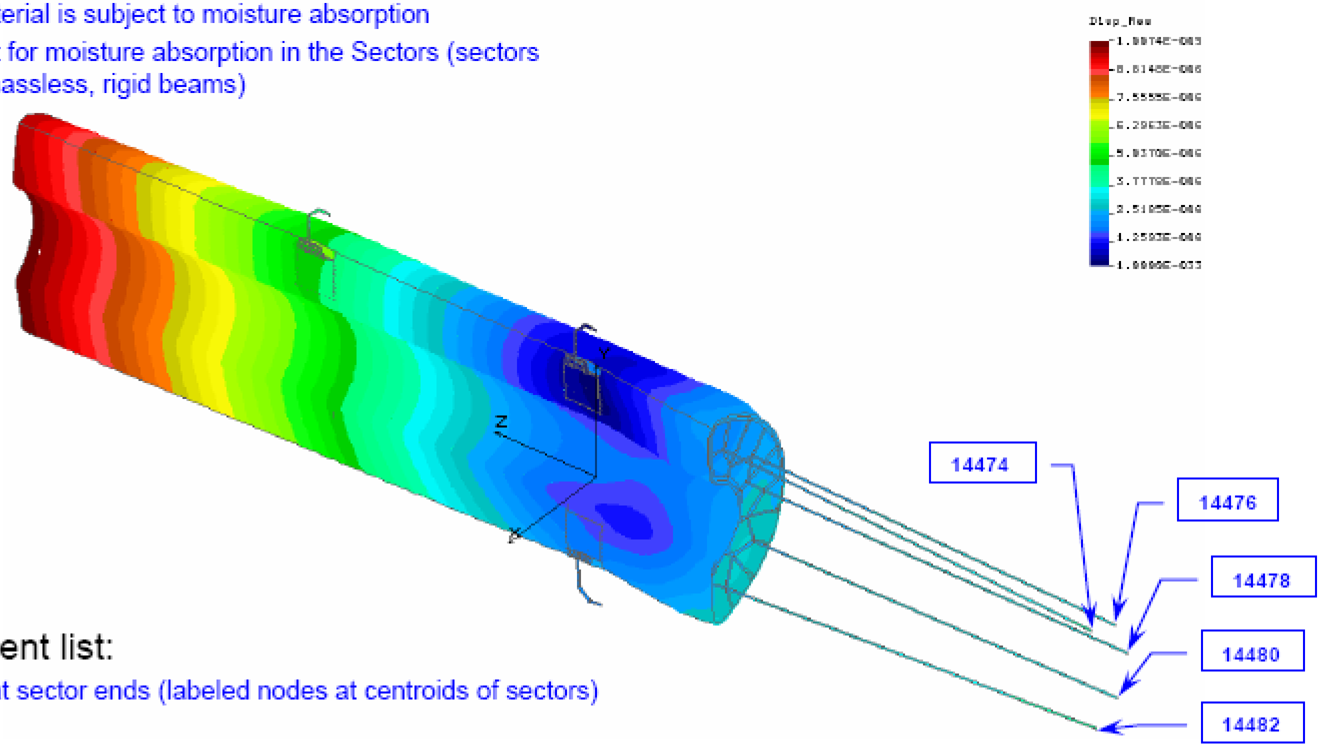
ladder to sector tooling fixtures (4 stations)

STAR HFT



D-Tube FEA – Displacements from Moisture Absorption

- Resultant displacements due to Moisture absorption:
  - Only YSH-50 material is subject to moisture absorption
  - Does not account for moisture absorption in the Sectors (sectors represented as massless, rigid beams)

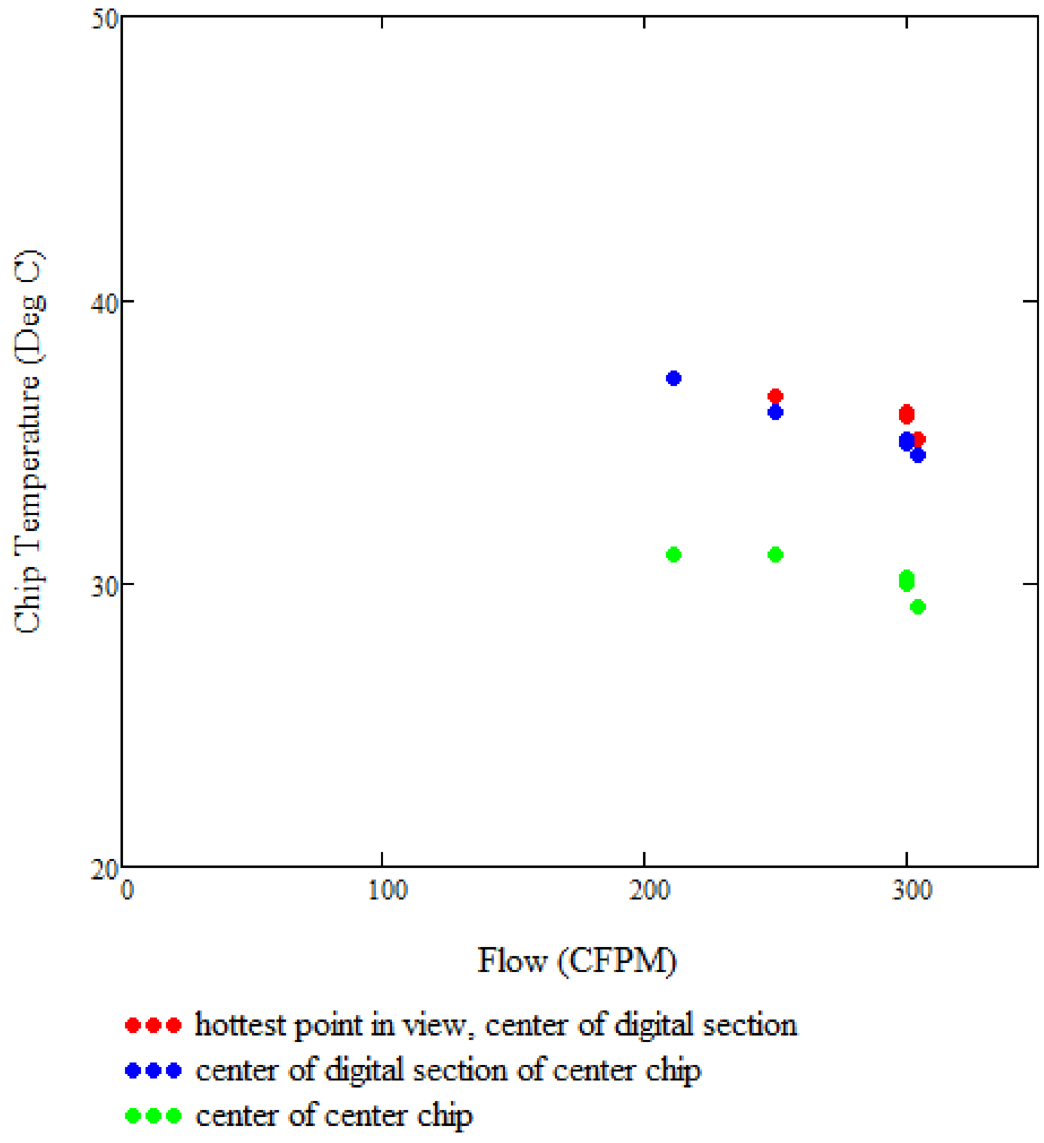


- Nodal-displacement list:
  - Displacements at sector ends (labeled nodes at centroids of sectors)
  - Units in meters

* Selection List 1   Load case 1

Node	UX	UY	UZ	RX	RY	RZ
14474	1.491e-006	-2.641e-006	-1.957e-006	-8.095e-006	-3.184e-006	-3.940e-006
14476	2.287e-006	-5.054e-007	-2.143e-006	-3.984e-007	-7.055e-006	-4.012e-006
14478	1.997e-006	3.264e-007	-2.270e-006	2.994e-006	-6.523e-006	-3.212e-006
14480	2.071e-006	1.190e-006	-2.318e-006	6.510e-006	-6.420e-006	-2.465e-006
14482	1.070e-006	2.936e-006	-2.270e-006	1.238e-005	-2.083e-006	-7.713e-006

Measured silicon temperature as a function of cooling air flow



The air flow in STAR as of February 2014 is 340 CFPM. So, the hottest point on the chip should be less than 35 deg C and the temperature in the pixel region of the chip should be less than 30 deg C.

The chip diode temperature is only read out on the eastern most end of the ladder. To within the accuracy of the measurement no temperature change is observed between ladder power on and ladder power off.

Log book reference:
https://skydrive.live.com/redir?page=view&resid=C9B8662B3A1439D3!548&authkey=!AG8fPDrdLvjbyZ0&wd=target%28PXL%20thermal.one%7c4D40E4DD-B650-49FB-B343-E4BF32A476D8%2fThermal%20with%20ECU%20fully%20connected%7c7DF36A31-D948-4DCF-87B1-BC168D5DE3CF%2f%29

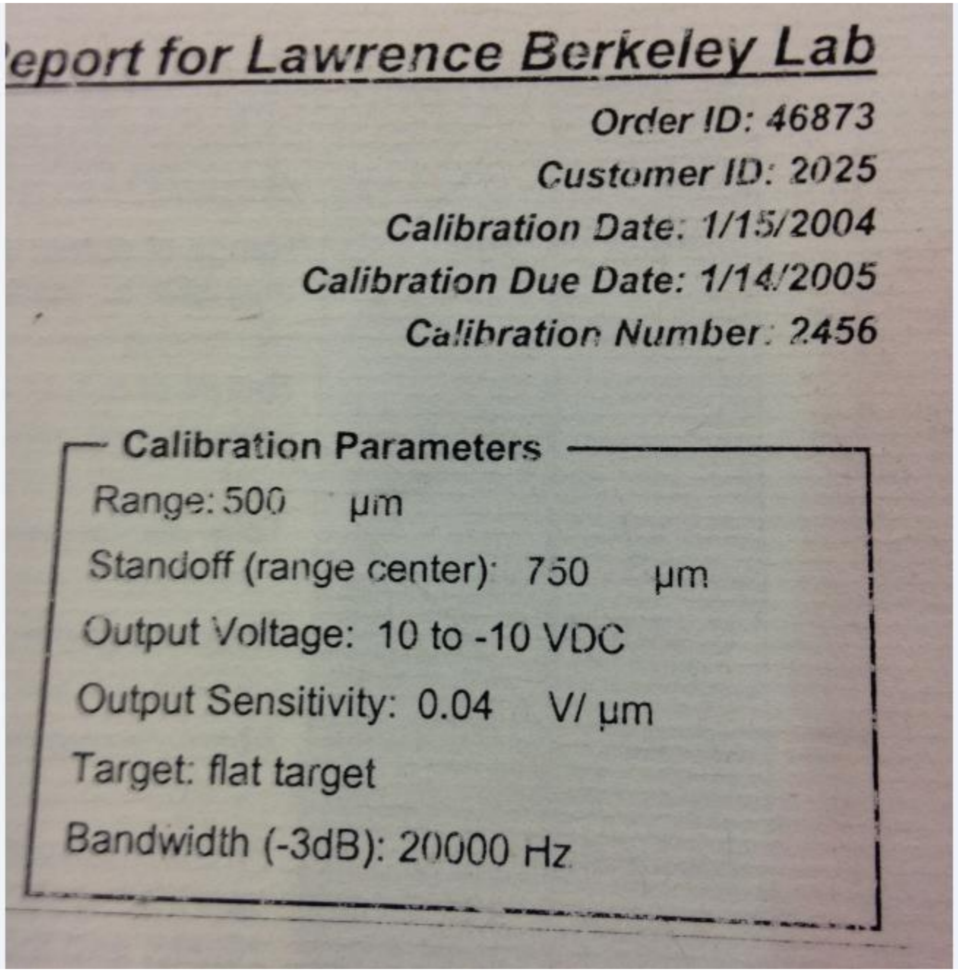
capacitive probe

http://www.lionprecision.com/

LION PRECISION
ISO9001 CERTIFIED

System Components
Probe Model: C1-A
Probe Serial: 030937-10
Driver Model: DMT20
Driver Serial: 031054-02
Channel: 0
Sensitivity Switch: NA

Peak to Peak Resolution: 50.0 nm
RMS Resolution: 2.0 nm

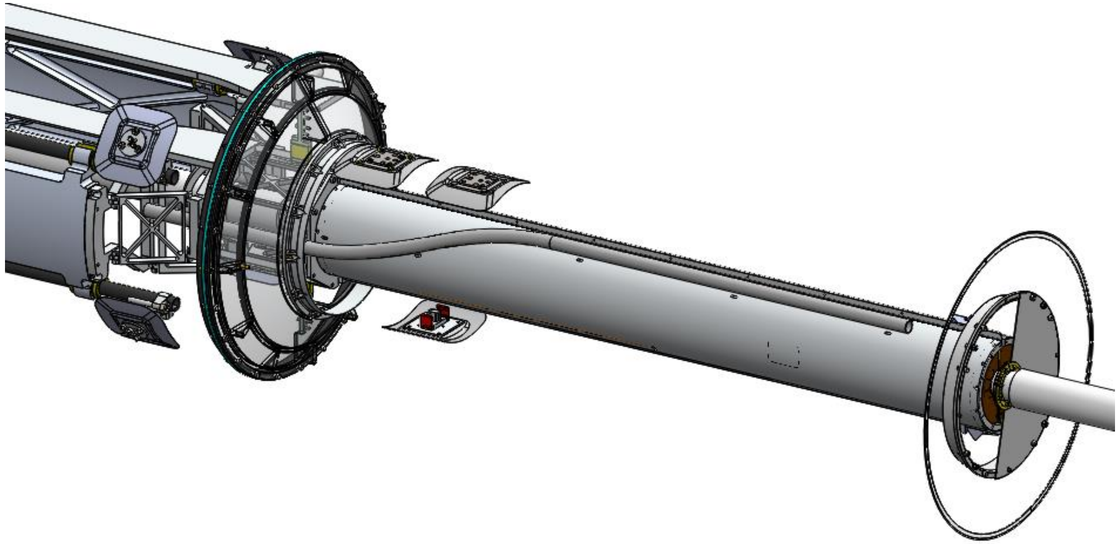


eport for Lawrence Berkeley Lab

Order ID: 46873
Customer ID: 2025
Calibration Date: 1/15/2004
Calibration Due Date: 1/14/2005
Calibration Number: 2456

Calibration Parameters
Range: 500 µm
Standoff (range center): 750 µm
Output Voltage: 10 to -10 VDC
Output Sensitivity: 0.04 V/ µm
Target: flat target
Bandwidth (-3dB): 20000 Hz

Insertable bake out jacket for the central portion of the beam pipe



2. Probability for picking the correct hit with an infinite search window using the chi-squared method

$$P_{ch} = \frac{1}{2 \cdot \pi \cdot \sigma_x \cdot \sigma_y \cdot \rho + 1}$$ eq. 2

Note, as expected eq. 1 reduces to the **closest hit form** when $\sigma_x = \sigma_y$

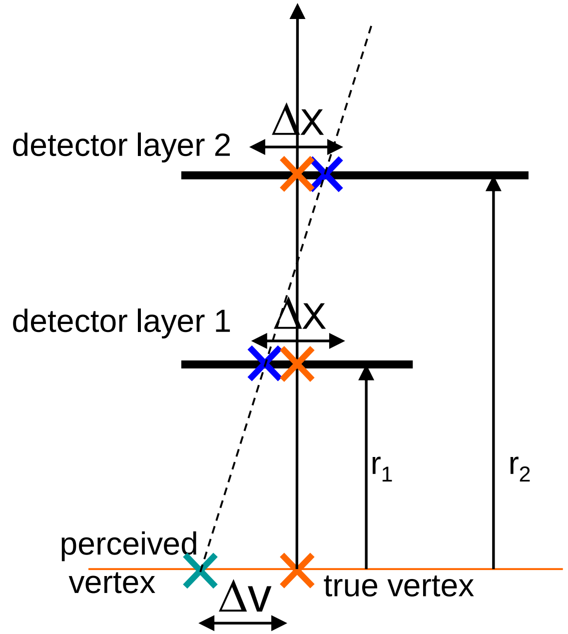
vertex projection from two points

expectations for the HFT pixels

pointing resolution = (13 ⊕ 19GeV/p·c) μm

from detector position error

$$\Delta v = \Delta x \bullet \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$



from coulomb scattering

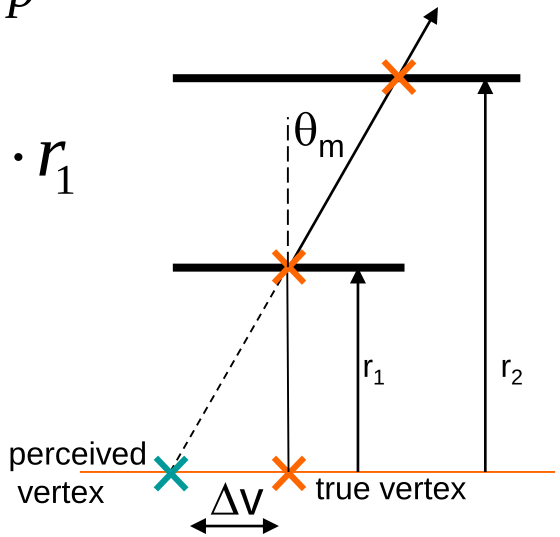
first pixel layer

$$X_0 = 0.3\%$$

more than 3 times better than anyone else

$$\theta_m = \frac{13.6Mev}{\beta \cdot c \cdot p} \cdot \sqrt{X_0}$$

$$\Delta v = \theta_m \cdot r_1$$



$\Delta xvib = 5\mu m$ detector vibration

$\Delta xcell = \frac{20\mu m}{\sqrt{12}} = 5.8 \cdot \mu m$ from pixel size, may be better using centroids

$$\Delta x = \sqrt{\left(\frac{20\mu m}{\sqrt{12}}\right)^2 + (5\mu m)^2} = 7.6 \cdot \mu m$$

$$\Delta x \cdot \sqrt{\frac{r1^2 + r2^2}{(r2 - r1)^2}} = 12.4 \cdot \mu m$$ first term

$\theta d \cdot r1 = 24 \cdot \mu m$ detector only

$\theta bp \cdot rbp = 12.5 \cdot \mu m$ beam pipe

second term

$$\sqrt{(\theta d \cdot r1)^2 + (\theta bp \cdot rbp)^2} = 27 \cdot \mu m$$ total second term