Raft-Grid Interface & Metrology

Large Synoptic Survey Telescope

P.O'Connor [BNL], A.Rasmussen [SLAC]

- **Kinematic coupling (KC) prototype results:**
  - **a) repeatability, measurement precision**
  - **b) Material options: raft vee - block and grid ball materials and coatings**
  - **c) Plan for testing**
- **Metrological transfer of RAFT to GRID:**
  - **a) GRID preparation**
  - **b) Raft Preparation**
  - **c) Pre-load load transfer: design update to transfer pre-load to grid**
  - **d) Master tooling and raft support during ass'y and test:**
  - **e) Concept for tooling through the process**
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  - **a) Requirements for testing for flatness of rafts and GRID during all phases (eg: assembly of rafts and integration into GRID)**
    - **i. warm**
    - **ii. cold**
    - **iii. warm at angles**
    - **iv. cold at angles**
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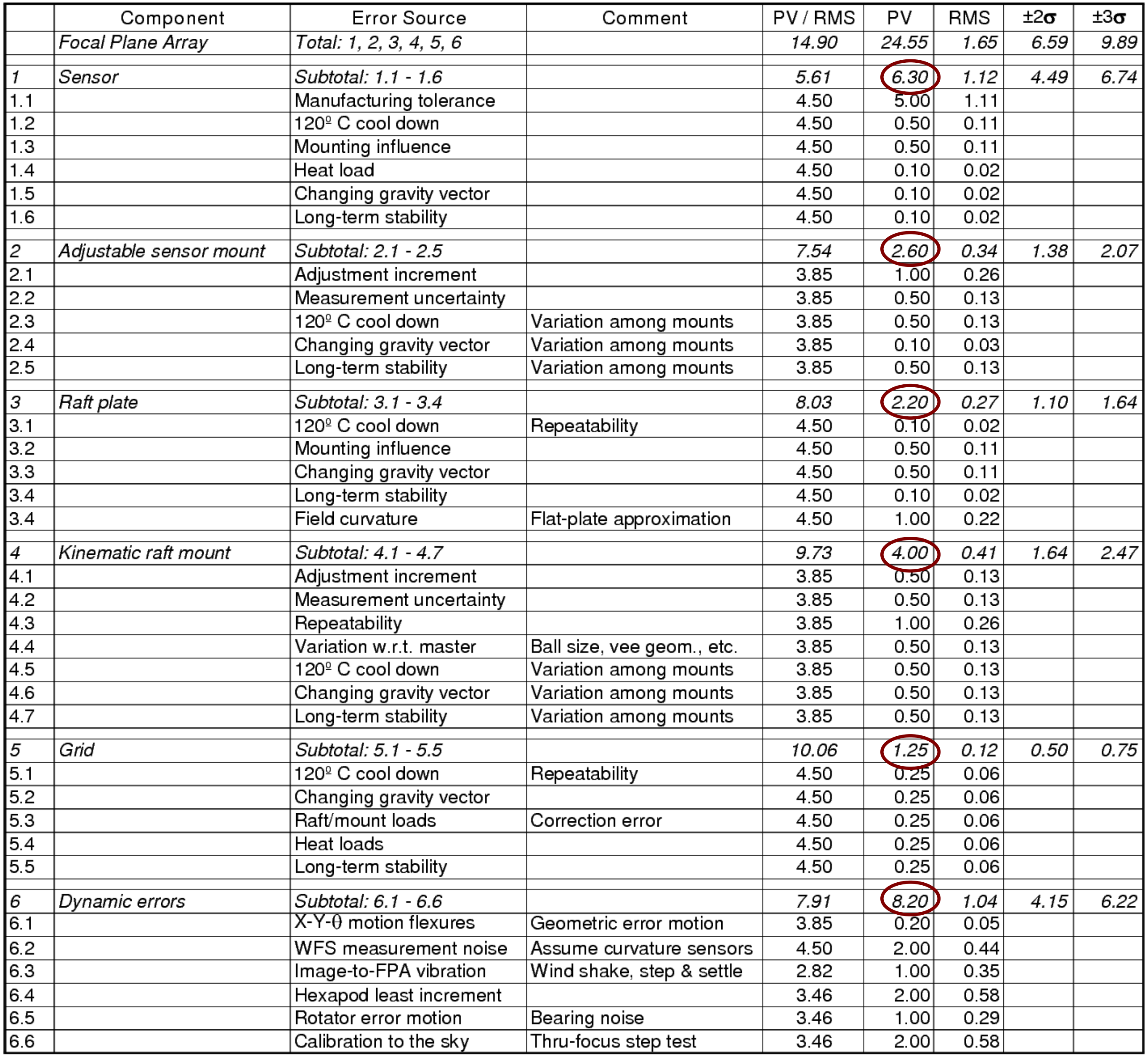
Current, Hierarchical FP flatness error budget (Layton Hale, LLNL)



	Component	Error Source	Comment	PV / RMS	PV	RMS	±2σ	±3σ
	Focal Plane Array	*Total: 1, 2, 3, 4, 5, 6*		*14.90*	*24.55*	*1.65*	*6.59*	*9.89*
1	*Sensor*	*Subtotal: 1.1 - 1.6*		*5.61*	*6.30*	*1.12*	*4.49*	*6.74*
1.1		Manufacturing tolerance		4.50	5.00	1.11		
1.2		120º C cool down		4.50	0.50	0.11		
1.3		Mounting influence		4.50	0.50	0.11		
1.4		Heat load		4.50	0.10	0.02		
1.5		Changing gravity vector		4.50	0.10	0.02		
1.6		Long-term stability		4.50	0.10	0.02		
2	*Adjustable sensor mount*	*Subtotal: 2.1 - 2.5*		*7.54*	*2.60*	*0.34*	*1.38*	*2.07*
2.1		Adjustment increment		3.85	1.00	0.26		
2.2		Measurement uncertainty		3.85	0.50	0.13		
2.3		120º C cool down	Variation among mounts	3.85	0.50	0.13		
2.4		Changing gravity vector	Variation among mounts	3.85	0.10	0.03		
2.5		Long-term stability	Variation among mounts	3.85	0.50	0.13		
3	*Raft plate*	*Subtotal: 3.1 - 3.4*		*8.03*	*2.20*	*0.27*	*1.10*	*1.64*
3.1		120º C cool down	Repeatability	4.50	0.10	0.02		
3.2		Mounting influence		4.50	0.50	0.11		
3.3		Changing gravity vector		4.50	0.50	0.11		
3.4		Long-term stability		4.50	0.10	0.02		
3.4		Field curvature	Flat-plate approximation	4.50	1.00	0.22		
4	*Kinematic raft mount*	*Subtotal: 4.1 - 4.7*		*9.73*	*4.00*	*0.41*	*1.64*	*2.47*
4.1		Adjustment increment		3.85	0.50	0.13		
4.2		Measurement uncertainty		3.85	0.50	0.13		
4.3		Repeatability		3.85	1.00	0.26		
4.4		Variation w.r.t. master	Ball size, vee geom., etc.	3.85	0.50	0.13		
4.5		120º C cool down	Variation among mounts	3.85	0.50	0.13		
4.6		Changing gravity vector	Variation among mounts	3.85	0.50	0.13		
4.7		Long-term stability	Variation among mounts	3.85	0.50	0.13		
5	*Grid*	*Subtotal: 5.1 - 5.5*		*10.06*	*1.25*	*0.12*	*0.50*	*0.75*
5.1		120º C cool down	Repeatability	4.50	0.25	0.06		
5.2		Changing gravity vector		4.50	0.25	0.06		
5.3		Raft/mount loads	Correction error	4.50	0.25	0.06		
5.4		Heat loads		4.50	0.25	0.06		
5.5		Long-term stability		4.50	0.25	0.06		
6	*Dynamic errors*	*Subtotal: 6.1 - 6.6*		*7.91*	*8.20*	*1.04*	*4.15*	*6.22*
6.1		X-Y-θ motion flexures	Geometric error motion	3.85	0.20	0.05		
6.2		WFS measurement noise	Assume curvature sensors	4.50	2.00	0.44		
6.3		Image-to-FPA vibration	Wind shake, step & settle	2.82	1.00	0.35		
6.4		Hexapod least increment		3.46	2.00	0.58		
6.5		Rotator error motion	Bearing noise	3.46	1.00	0.29		
6.6		Calibration to the sky	Thru-focus step test	3.46	2.00	0.58		

Table 1 Focal-plane-array error budget. All errors are in units of micrometers (0.001 mm).

sensor

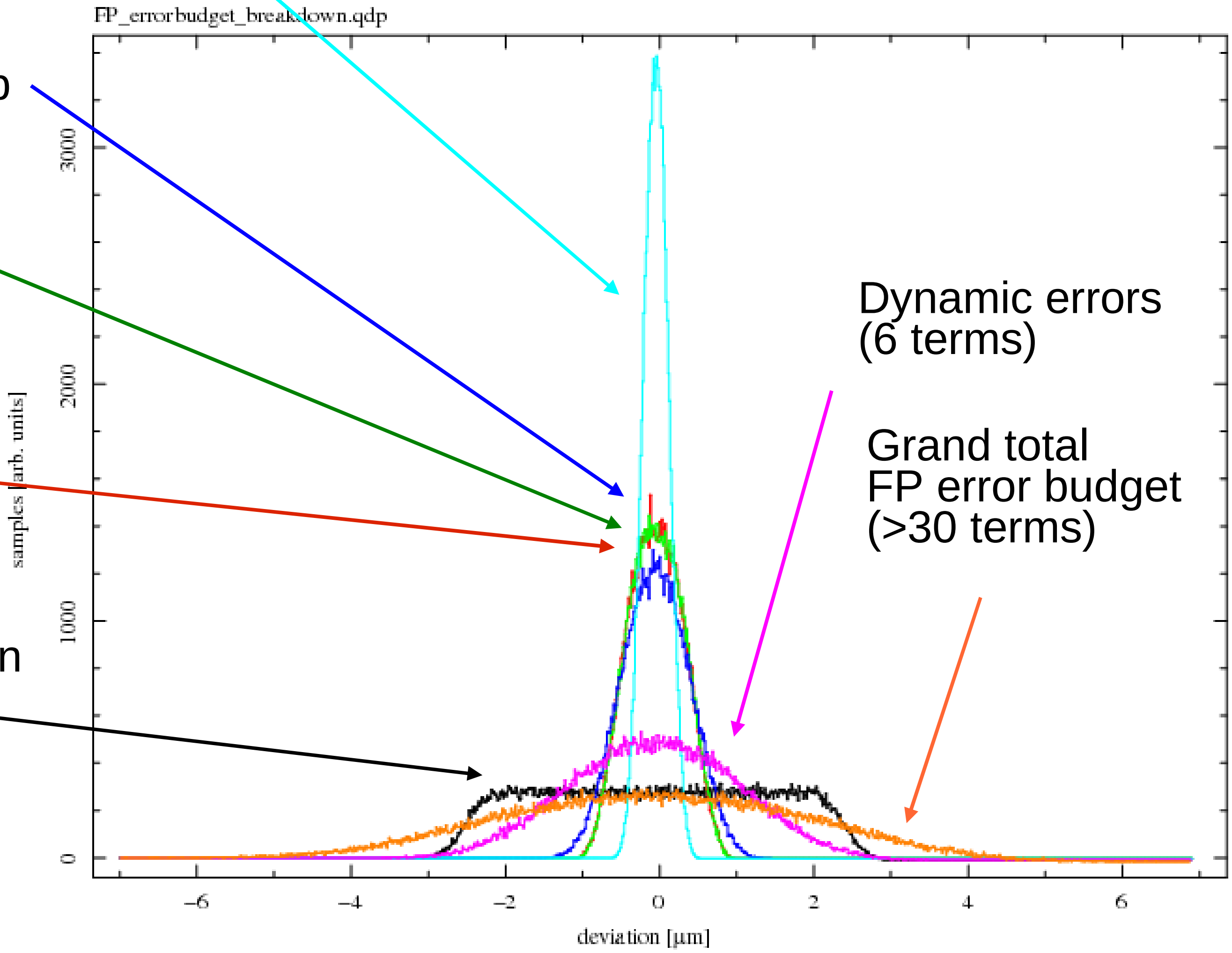
(adj.) sensor mount

Raft Plate

Kinematic mount (Raft)

Grid

Dynamical errors



Grid contribution
(5 terms)

Kinematic raft mount contrib
(7 terms)

Raft plate contribution
(4 terms)

Adj. Sensor mount contrib
(5 terms)

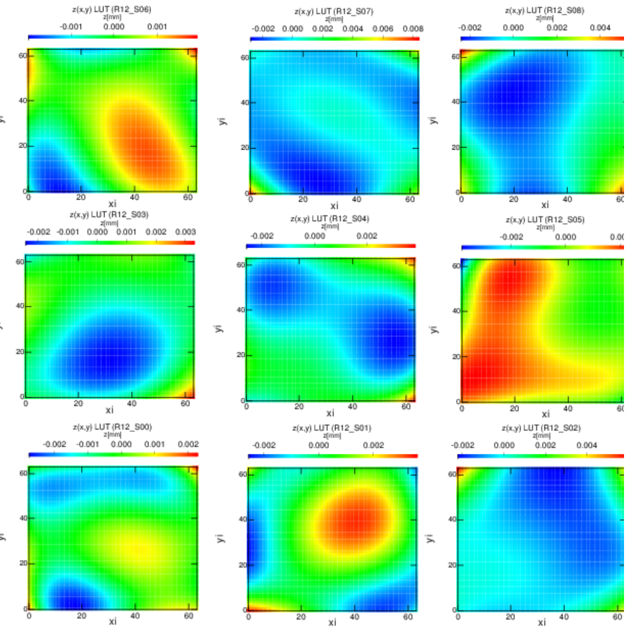
Sensor level contribution
(6 terms)

Dynamic errors
(6 terms)

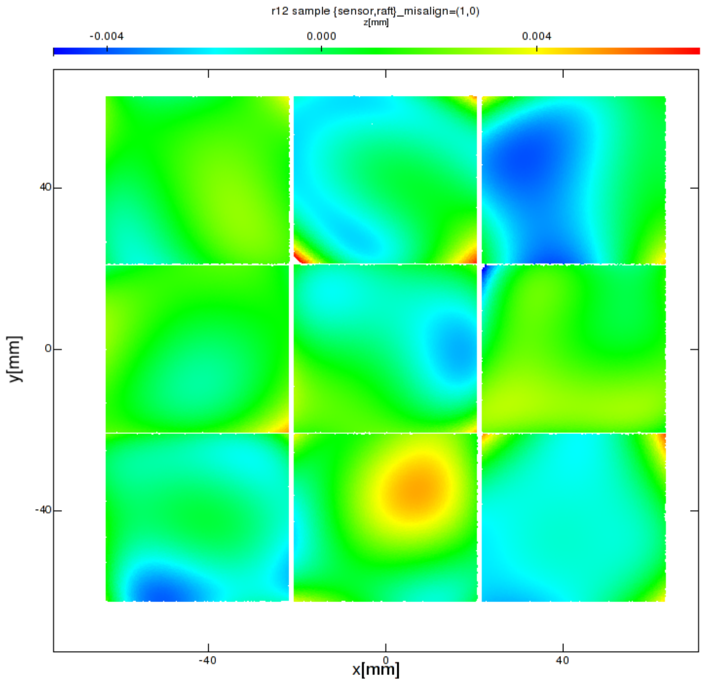
Grand total
FP error budget
(>30 terms)

A “realistic” (?) LSST_FP: hierarchical/modular design

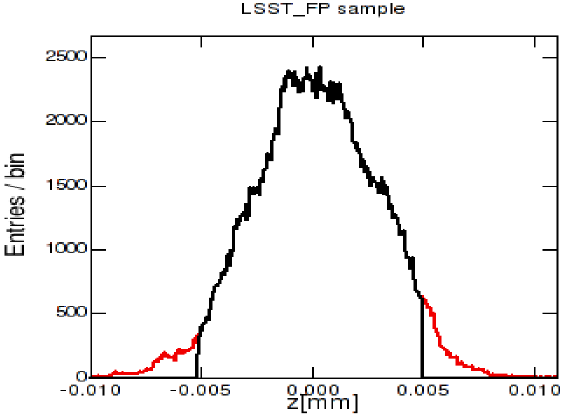
Large Synoptic Survey Telescope



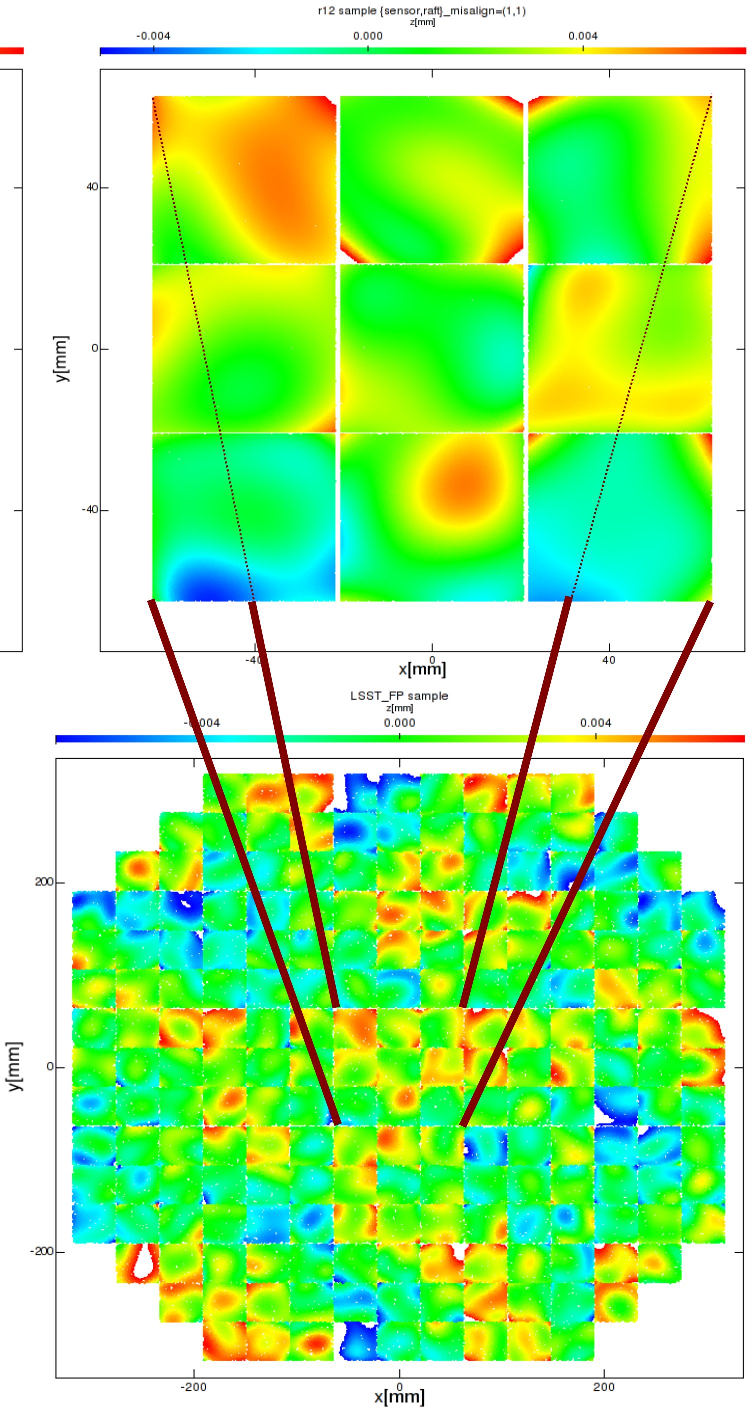
Metrology of individual sensors
(e.g. Fizeau interferograms)



Noninterferometric, noncontact
metrology of an assembled raft.
(phase ambiguity across gaps)



>93% with |z| < 5μm



Kinematic Mount (KM) prototyping using a “raft prototype”

Characterize components (establish wear-in cycle and resulting stability for candidate mounting hardware: 6 constraint mount, maximally compliant to thermally induced differential expansion..

Kinematic mount “vees” (90 deg):
- Ti
- A200
- Inconel

The “Raft”

Ball locator “cups”

Commercially available grade 5, 8mm balls (nom. 5µ” control)

Si3N4
HRC 80 (typ.)

Tungsten Carbide (WC)
56-70 HRC

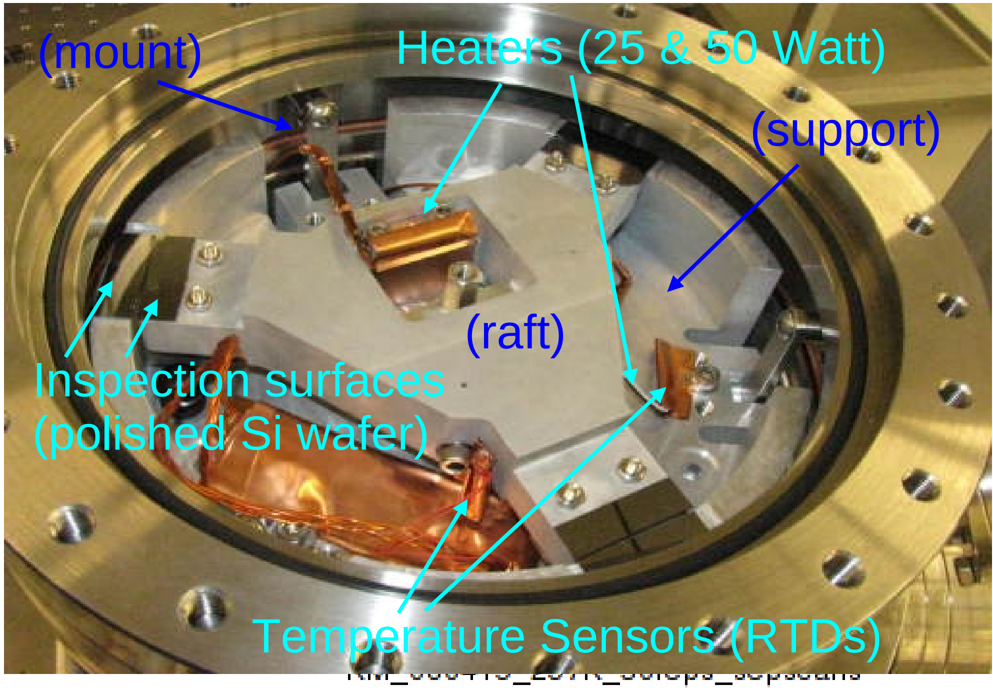
SS 440
HRC 62

Goals:

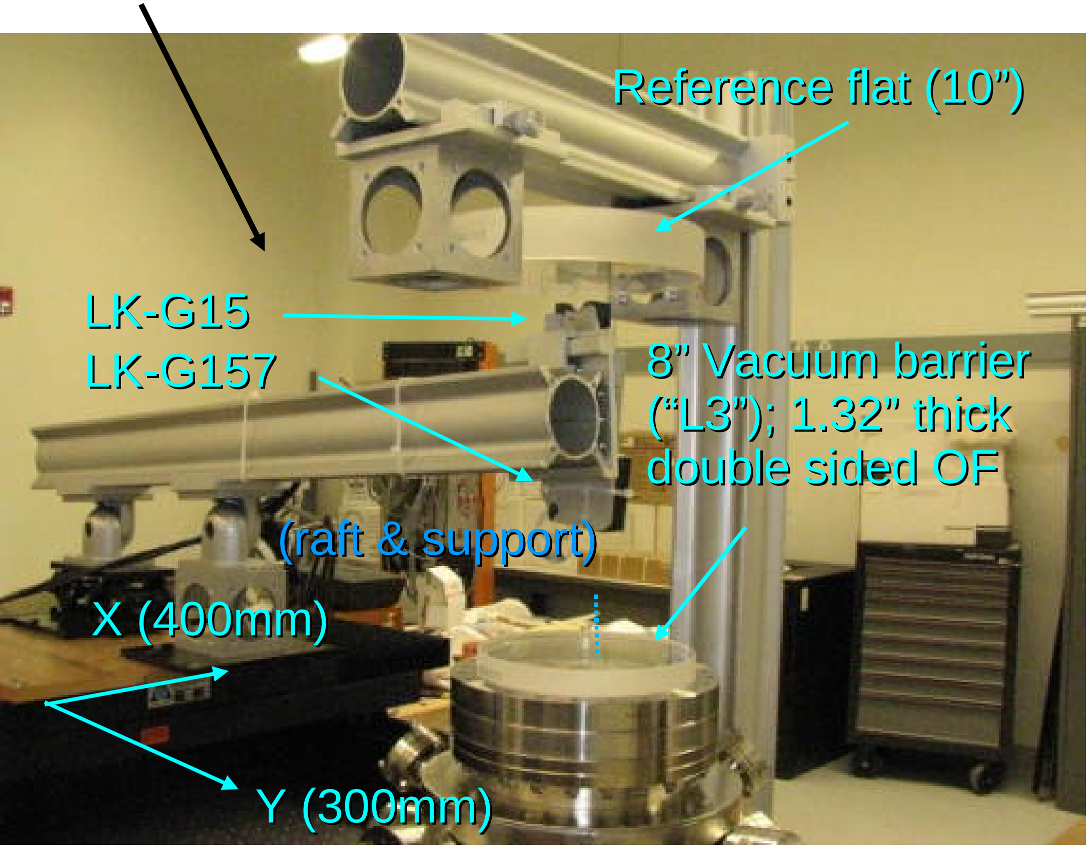
Guide materials choice, surface finish/coating that minimize impact, static load and frictional wear – which can frustrate co-alignment efforts across sensors and rafts in LSST focal plane.

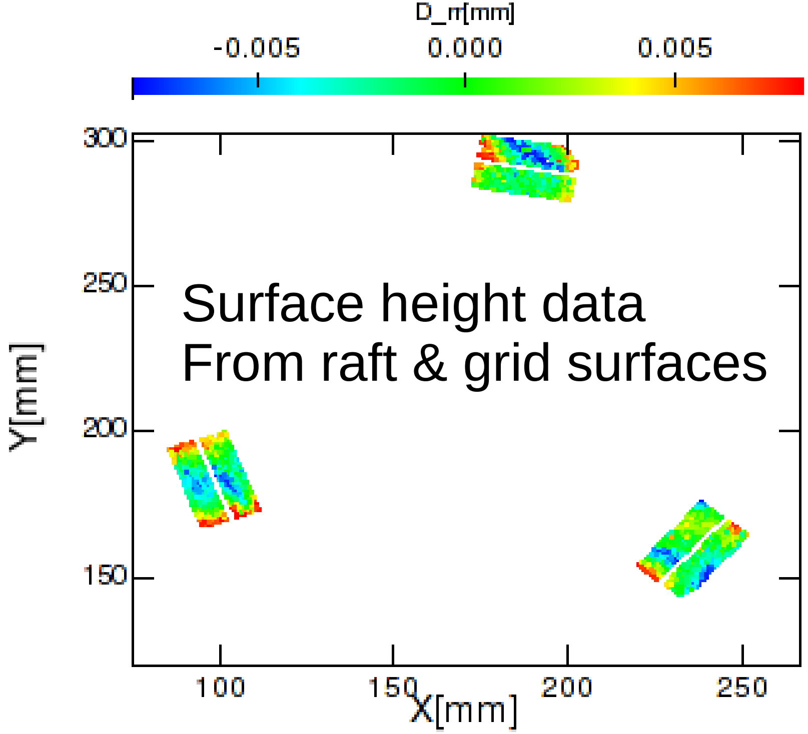
Testing facility for KM studies (a *thermo-vac/*metrology facility bearing minor resemblance to LSST camera)

Raft/Prototype to test kinematic mount components under representative conditions

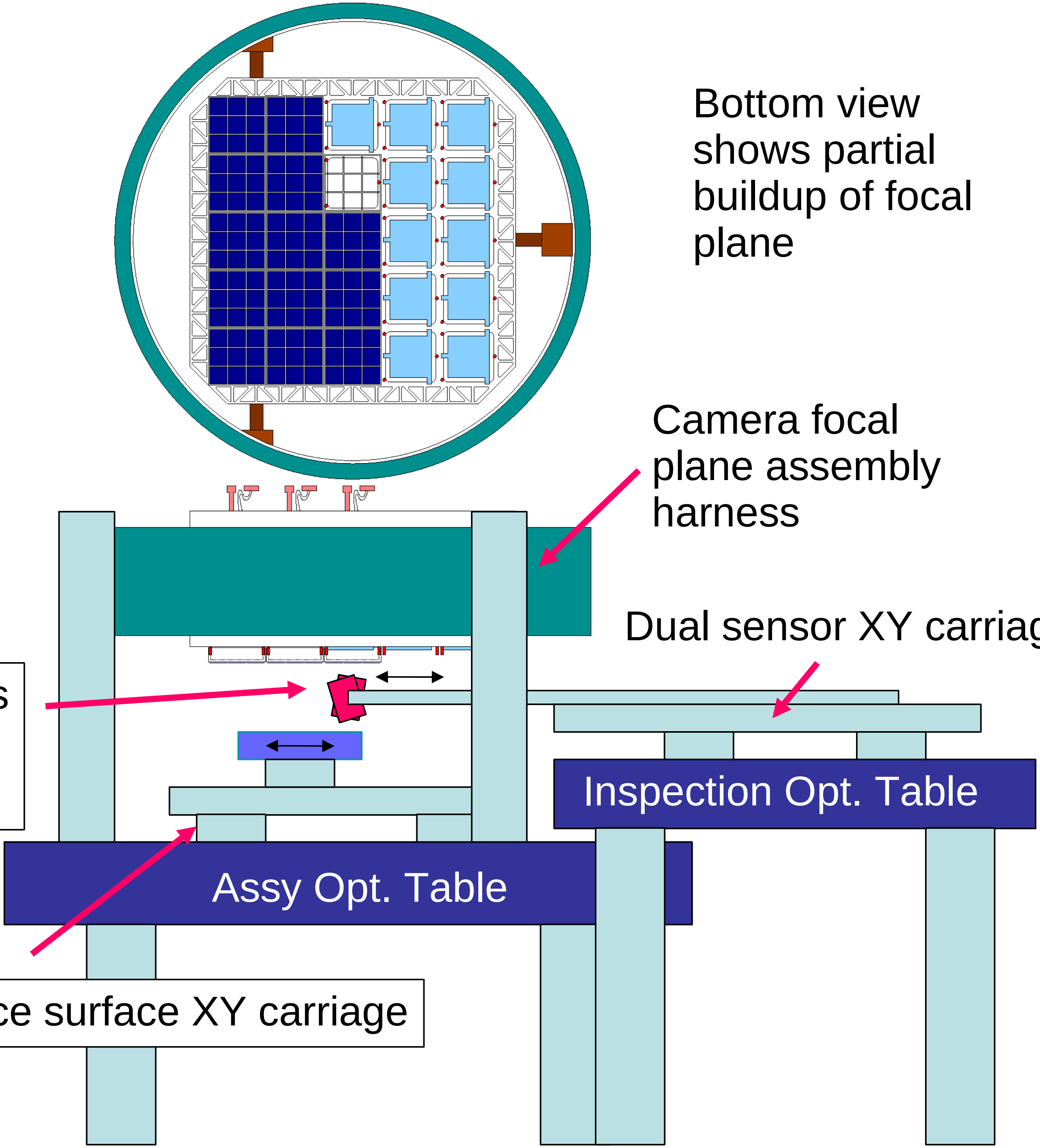


Differential displacement sensor metrology robot & thermal/vac sample holder





Surface height data
From raft & grid surfaces



Bottom view shows partial buildup of focal plane

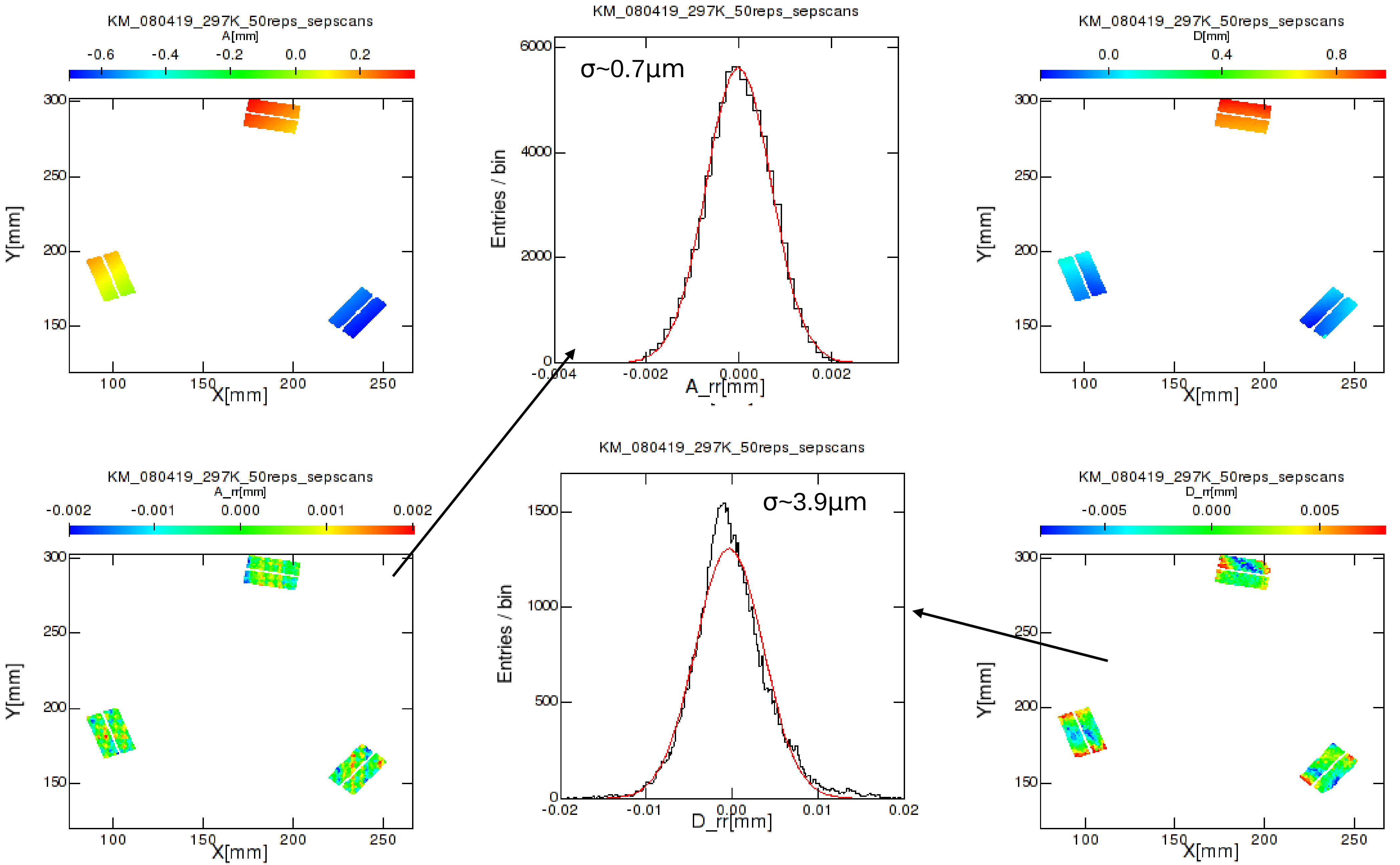
Camera focal plane assembly harness

Dual sensor XY carriage

Displacement sensors (up & down looking)

Reference surface XY carriage

Sample data obtained in the KM-RP thermo-vac/metro facility


σ~0.7μm

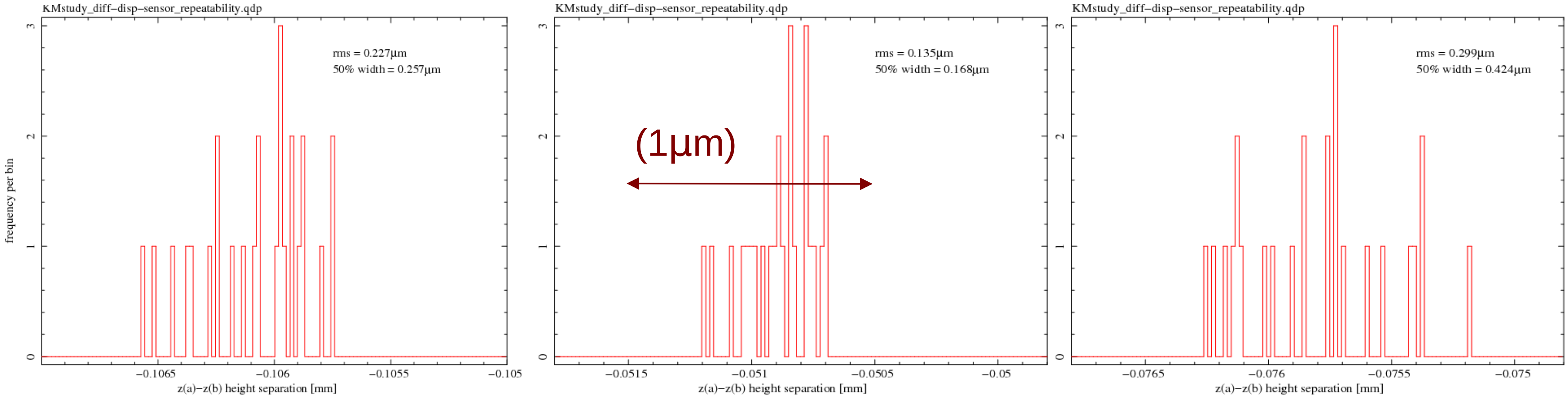
σ~3.9μm

KM tests in Thermo/Vac metrology facility

The tests we've done

- stability/repeatability under “constant” conditions:
  - measure raft prototype (RP) heights *wrt* base many times
  - ambient/atmosphere or under thermal control (under vacuum & thru vacuum barrier *e.g. L3)*
- Witness KM component wear-in across many mating/de-mating operations
  - RP heights *wrt* base as a function of handling cycle
- Witness KM component wear-in across controlled “scrubbing” under preload, ~10G or 40lb
  - Repeatable, differential expansion induced frictional translation of the ball's contact points against the vee-block surface

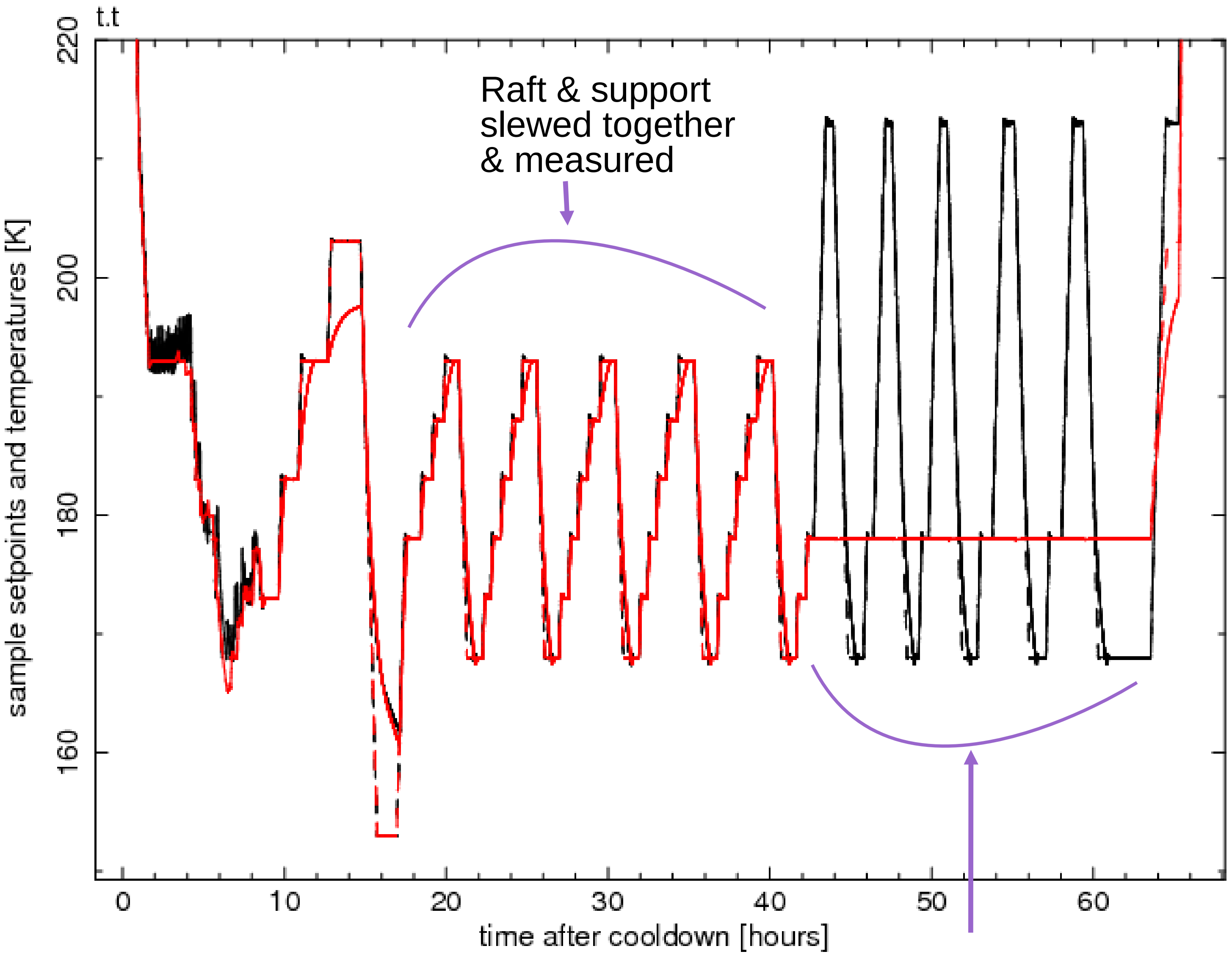
Established measurement precision: repeatability 1)



- Representative conditions for measurement (thru-window, under vacuum)
- Distributions of fiducial z-height pair difference measurements performed by referencing off of an opposing optical flat ("differential non-contact metrology")
- Measurement samples were inside an evacuated vacuum chamber at room temperature; 25mm from a 34mm thick double sided optical flat vacuum barrier (e.g., "L3")
- Shown are 3 surface height difference distributions, performed 25 times each over 8 hours (6 minutes/scan, producing $<\sigma(\Delta z)>$ ~ 0.22µm) [$<\sigma>$~0.27µm @3min/scan]

Witness KM components wear-in:

2)



Raft & support slewed together & measured

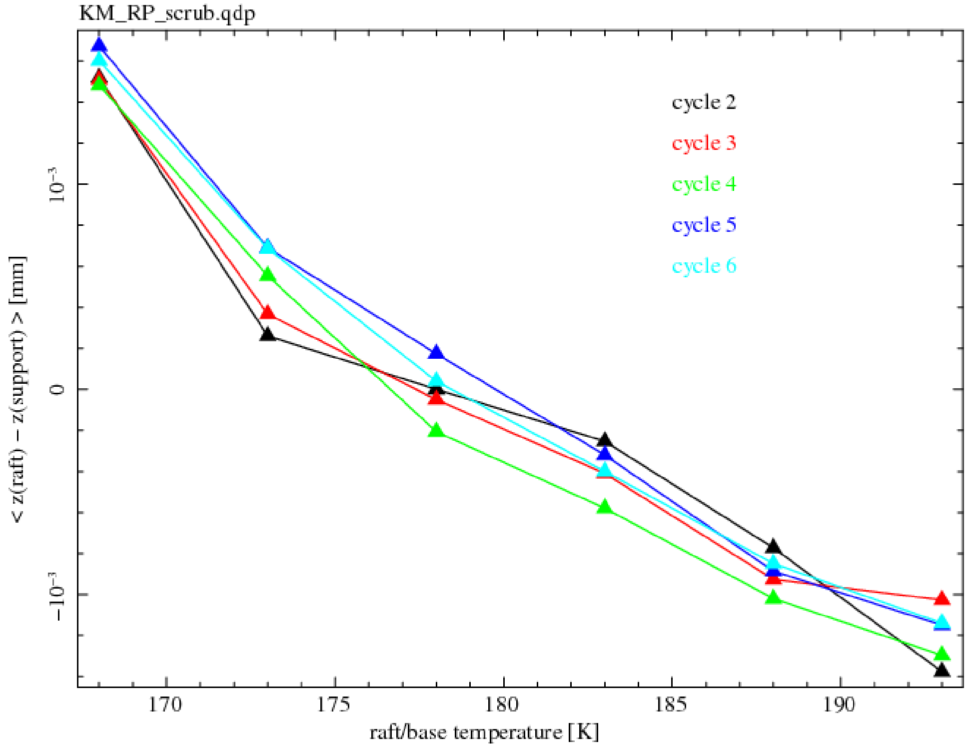
Raft temperature is held constant while support is slewed: controlled abrasion & stress under preload

2)

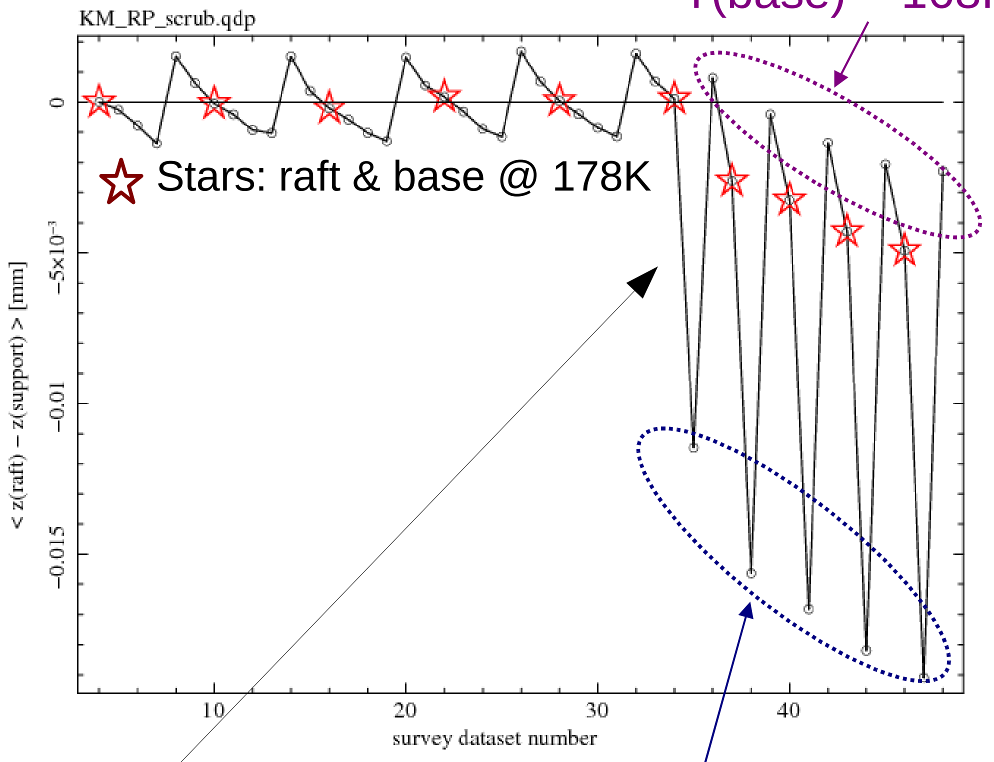
Temperature slew results (controlled KM wear)

(Average of 3 raft datum surfaces relative to nearby datums on base) Note correspondence to temperature profile on previous page

T(raft) = T(base): slope gives relative expansion for different materials in 15mm high stack



T(base) = 168K



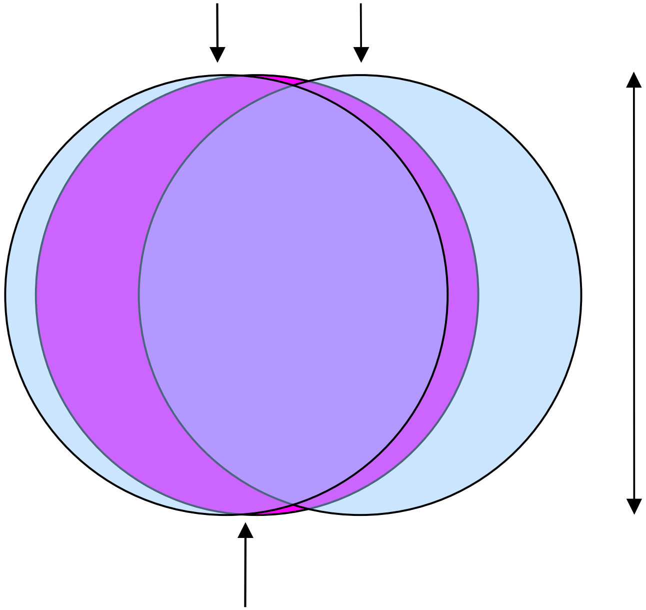
☆ Stars: raft & base @ 178K

T(base) = 213K

Real wear (is ball rolling or abrading?) ~ 1µm / ±60µm back-and-forth motion under load

A cartoon explanation

2)



T(base)=168K

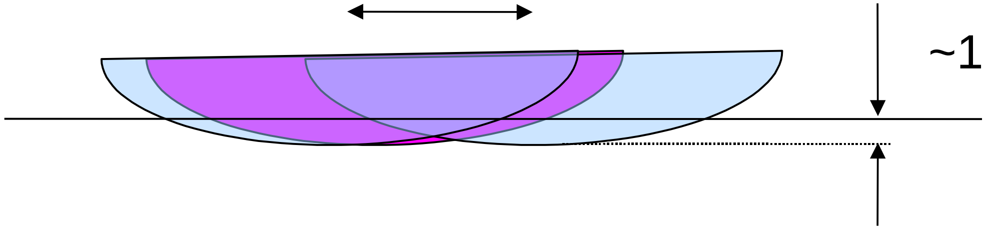
T(base)=213K

Contact “footprint”
@ 10 lbF: ~220µm

T(raft)=T(base)=178K

'stroke' over thermal cycle: Δ~60µm

(impression **not** to scale)



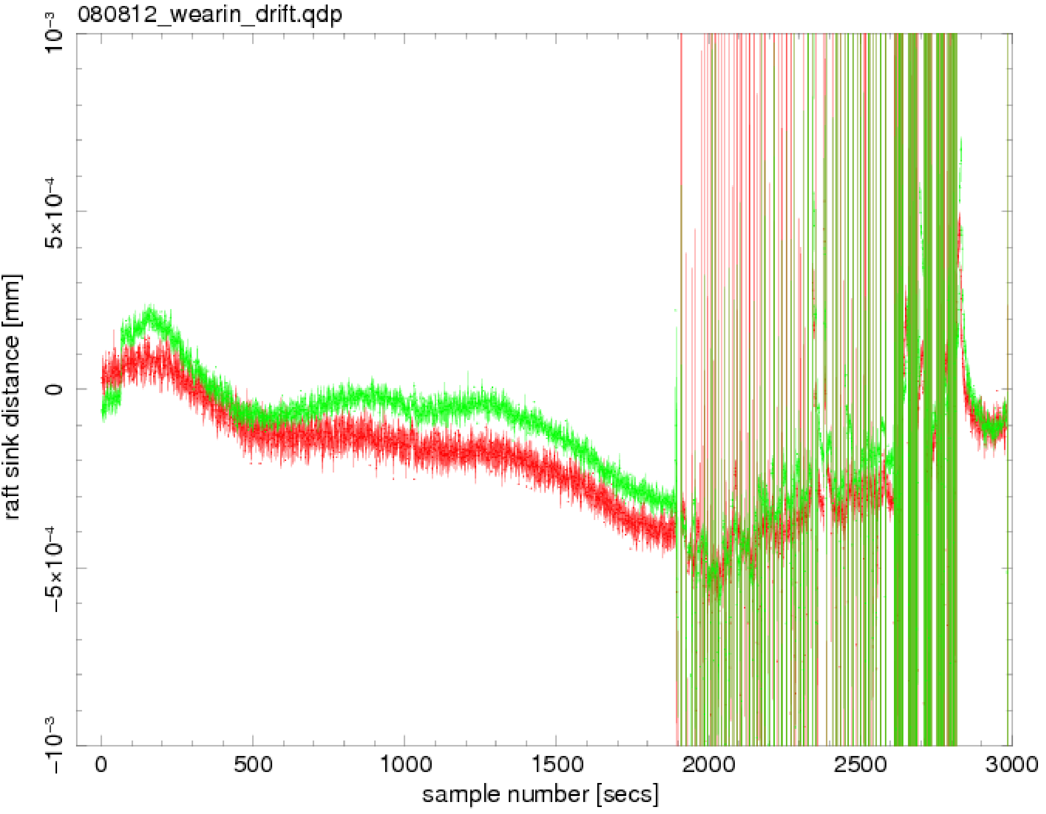
~1.6µm @ 10 lbF, 8mm balls, Ti surf.

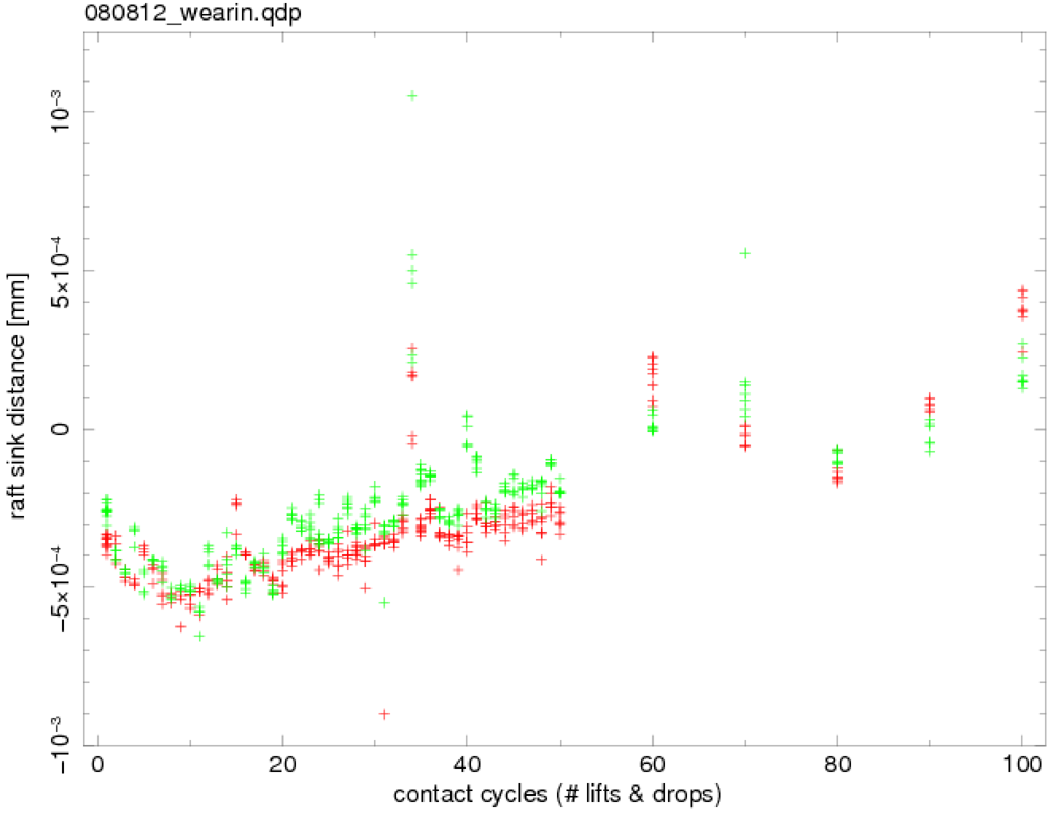
=> Abrasive wear of ~1µm per thermal cycle may not be so crazy, given ΔT induced scrubbing (under load) of ~60µm and static deformation of ~1.6µm (Brinell hardness ~716MPa)

Witness wear-in by handling: repeated engagement/disengagement of KM using a lifting fixture.

3) Using the multiplexed AD7747 capacitive sensors for faster feedback

What could be a straightforward measurement is somewhat difficult to interpret..

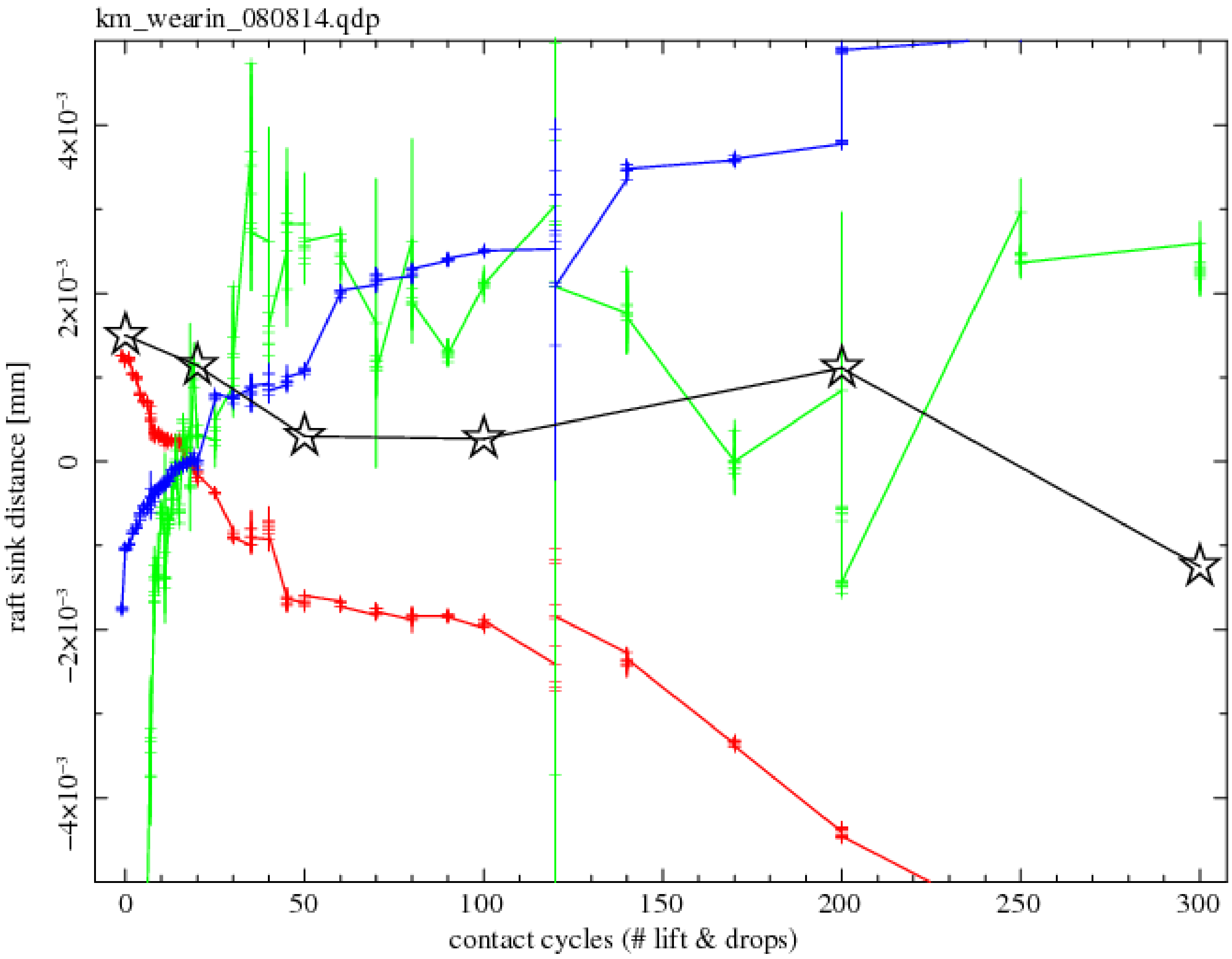




Repeat, this time with a 'rapid' sanity check, provided by the displacement sensor system

3)

NB. drift values exceed those from previous page, and haste applied in obtaining displacement sensor feedback degrades quality of this measurement.



.. Do Over!!

Lessons learned--

- Careful alignment of raft with lifting fixture
- Operate deliberately
- Consider automating contact cycles
- Don't underestimate care required in precise mating of KM components: dragging, scraping, dinging may be occurring even with moderate misalignment

Plan for testing: KM components study by PDR/CD1

- Baseline is now established for improving on
- Wear-in from handling is currently inconclusive, but *probably* with $\Delta < 0.5\mu m$ over 100 (careful) contact cycles
- Improve surface quality and obtain more results
  - OTS balls are already ground to high smoothness – improvement is unlikely
  - Grind or lap existing vee block surfaces to near-mirror finish (Ti, A200, Inconel)
    - Include vee blocks from SiC stock (more representative material) in tests
  - Investigate effect of thin, hard low-friction coatings (e.g. PVD coatings of MoS_2, graphite, DLC)
- Increasing ball diameters would help but there's little room to spare in cryostat/grid. (currently using 8mm)

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  b) **Methodology for testing for flatness of rafts and GRID during all phases (eg: assembly of rafts and integration into GRID)**

Modular design for Science Rafts and GRID

- Rafts: 21 + spares, identical
- Corner rafts: 4 unique
- Baseline consideration:
  - Rafts each carry 9 unique sensors whose surfaces fit within the same 6.5µm wide band, centered on a plane that is parallel to and offset by [TBD mm] from the reference plane formed by 3 apexes of the (kinematic mount) precision ball components. *when preloaded*,
  - The focal plane optical bench (GRID) will feature an array of precision ball KM components with apexes falling within a 1.5 µm wide band, centered on a plane *when KM balls are pressed against the GRID at the prescribed preload, "raft" dummy masses are installed into the GRID, and GRID is at operating orientation and temperature (T~163K [TBC])*.

Sensor Vendor requirements are weaker:

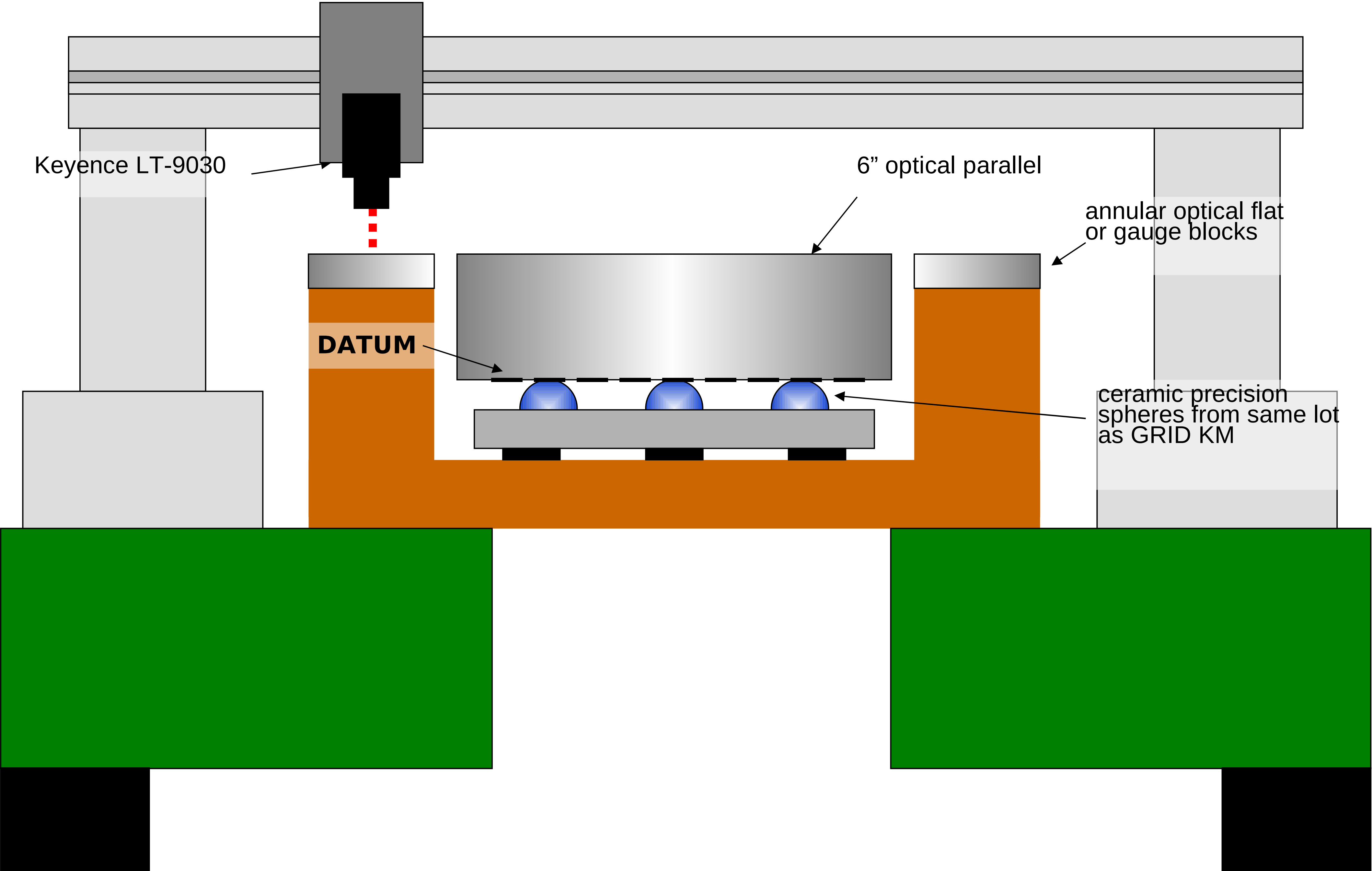
- 2.3.2.4.3. The CCD imaging area flatness, excluding the dead area between the last imaging pixel to the cut line, shall be within 5µm peak-to-valley over 100% of the imaging area.
- 2.3.2.4.4. The mean CCD surface shall be parallel to the mounting surface to within 250µrad. ($\Delta z<10\mu m$ over 40mm) The mounting surface is assumed to be perfectly flat and to coincide with the package reference surface defined by appropriate mounting features.
- 2.3.2.4.5. The variation in z-height of the CCD surface from the mounting surface shall not exceed 10µm from packaged device to packaged device. ($|z_i(x,y)-z_j(x,y)|<10\mu m$ for any sensor pair i,j)
- ➔ To meet raft flatness spec additional shimming may be required at the raft level – with as much as $\Delta z \sim 10\mu m$ and $\Delta\theta \sim 250\mu rad$ applied to each sensor.
- ➔ To meet identical raft/parallelism requirement, a spec for substrate parallelism and corresponding shimming allowance would be followed (for raft substrates, which include KM vee components).

Proposed Raft Metrology

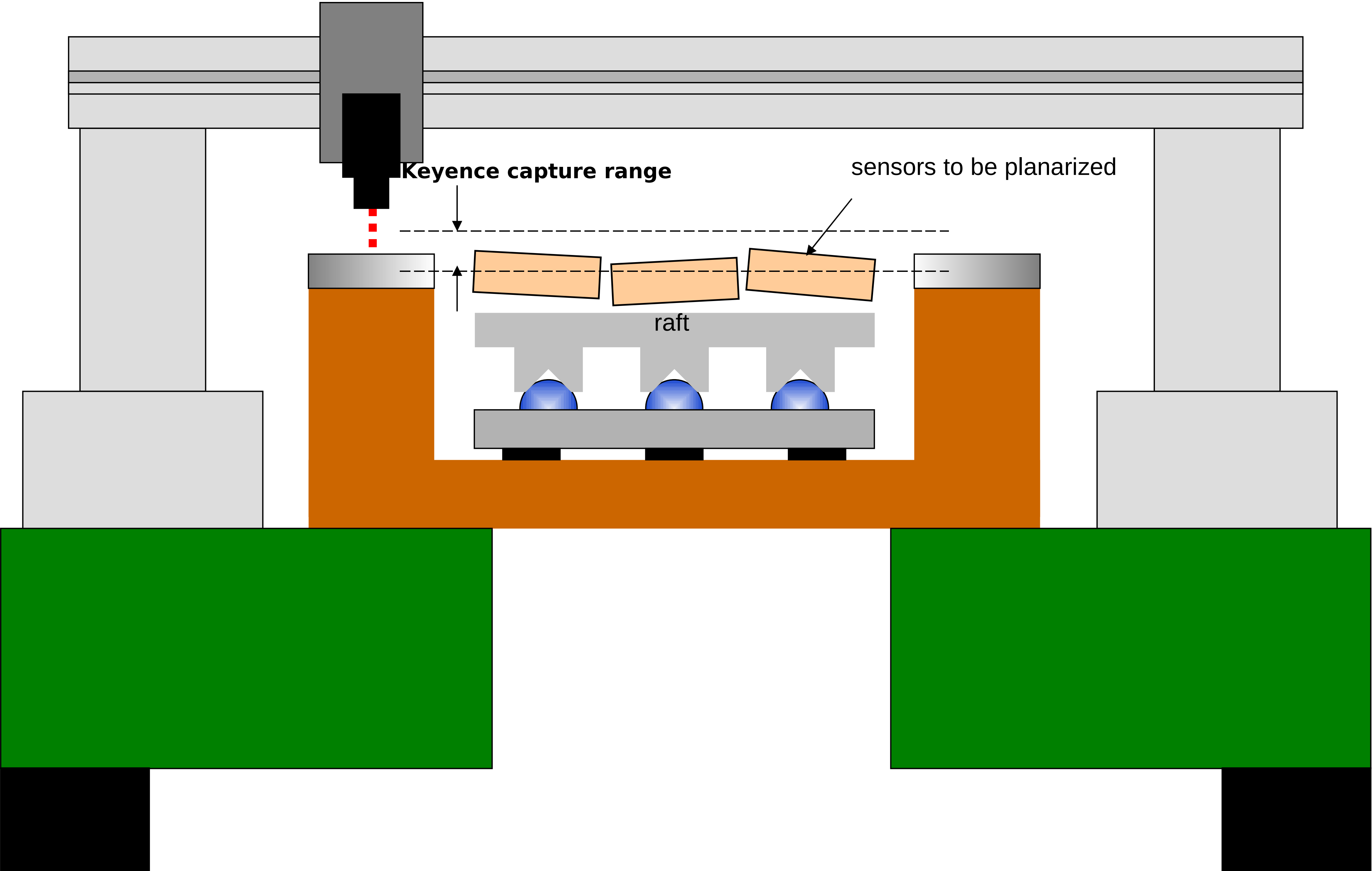
P. O’Connor, P. Takacs, S. Plate

BROOKHAVEN
NATIONAL LABORATORY

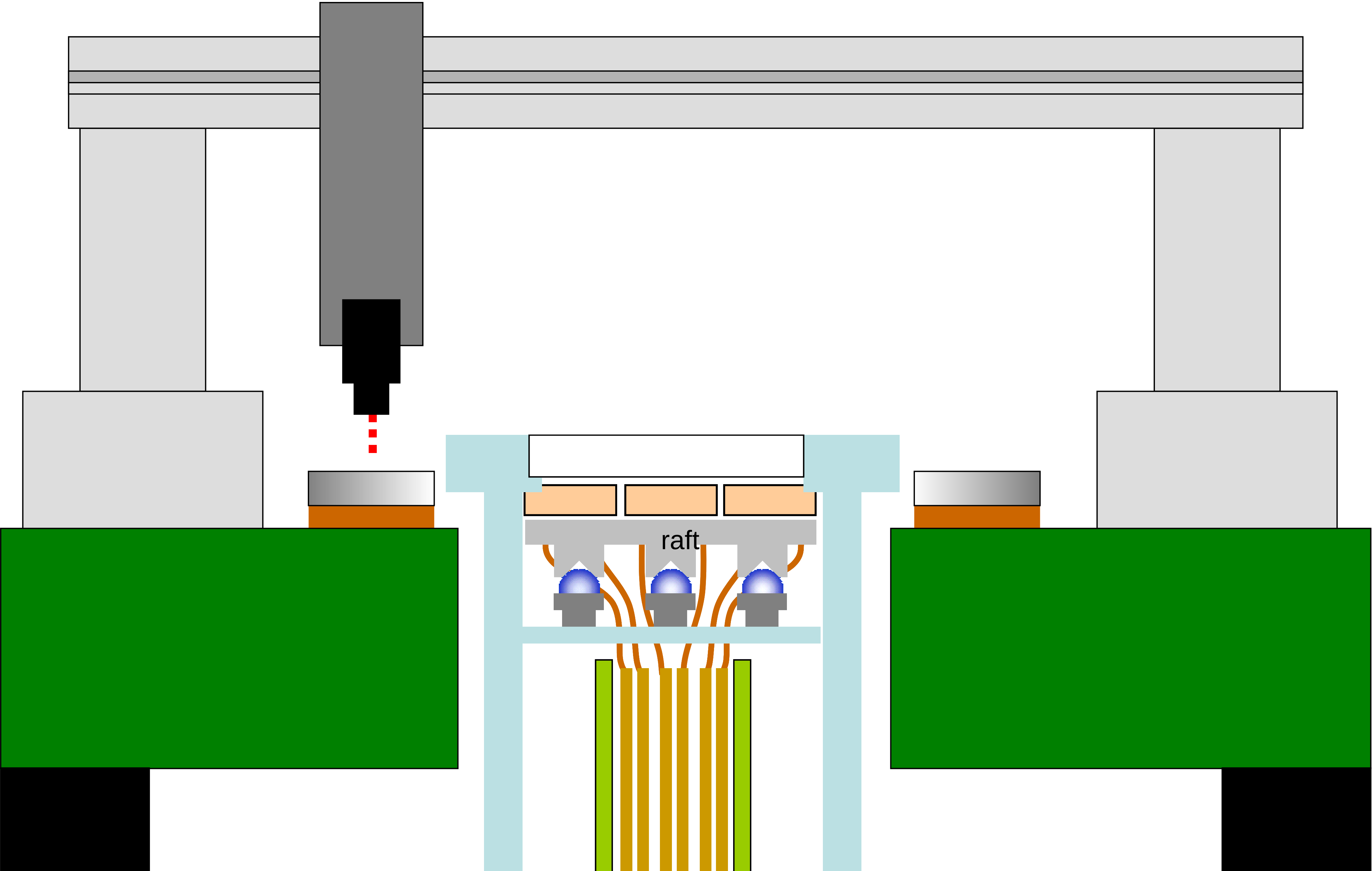
Parallel optical flat transfers plane of KM spheres to annular optical flat



Sensors adjusted to coincide with transferred DATUM



Raft metrology at -100C

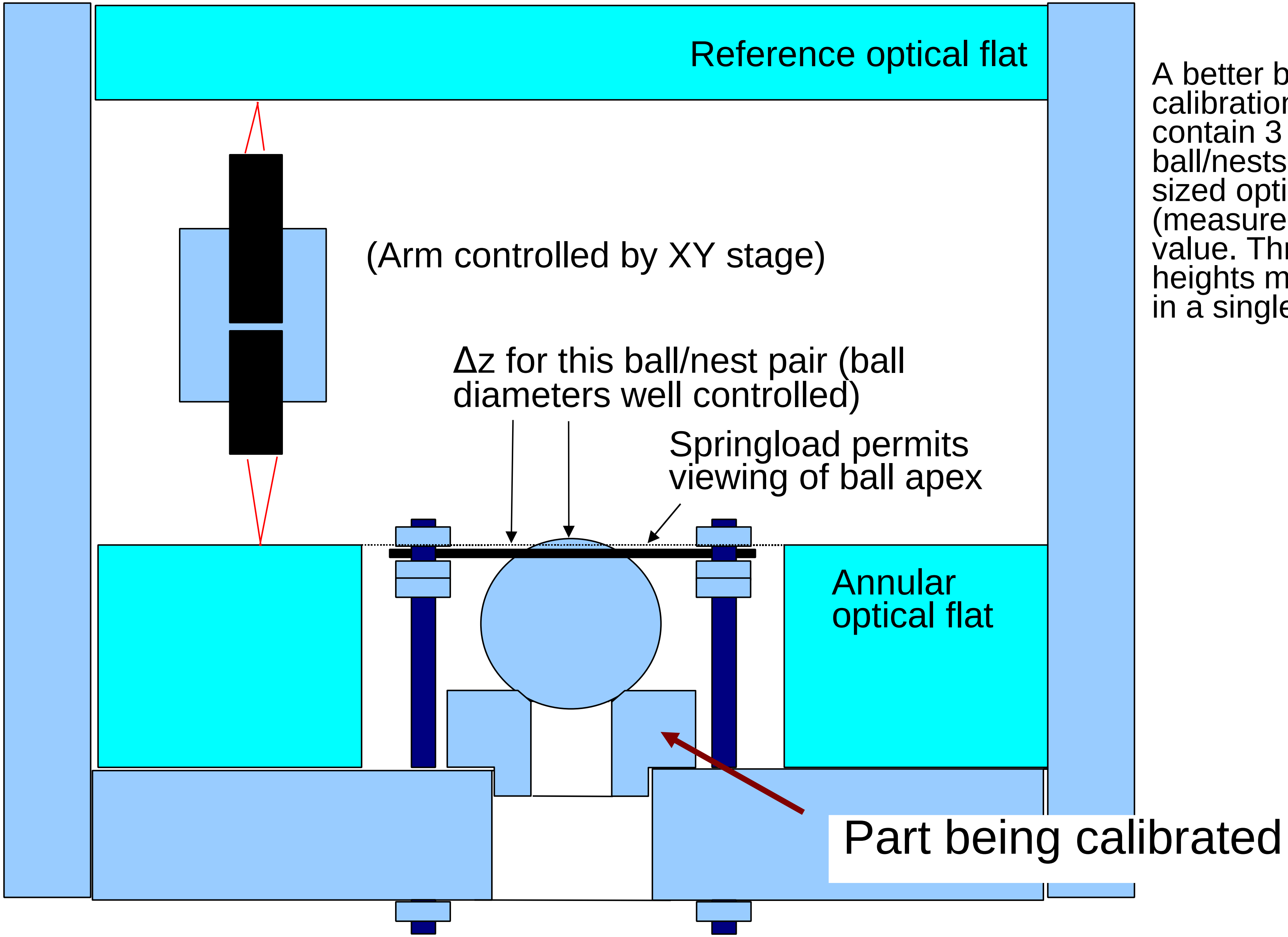


Follow the “identical raft” baseline:

- Establish a co-planar set of the KM precision ball apexes (each held with representative load or spring clip)**
  - Parts are pre-measured in a ball/nest calibration setup and sorted/binned according to the part's height (see next page)
  - Grade 5 balls have 5µ” diameter control (0.13µm), just below measurement precision for Keyence LK-G152 (not for our other sensors)
  - Substantial natural variation in nest height (or chamfer depth) should occur, even for identically produced parts (σ~10µm?)
  - Ball nest lots are produced with different nominal heights to provide natural variations that overlap with adjacent lots
  - ➔ An initial, arbitrary (but measured) set of ball/nests are installed (and loaded against Grid)
  - ➔ Grid surveys are performed: heights of ball apexes and local fiducials hosted by grid (reflective surfaces, locally flat) relative to an opposing optical flat (see following)
  - ➔ A parts “wish list” is generated: a desired modification for each location based on synthesized/stitched measurements produced under representative conditions
  - ➔ An updated set of ball/nests will be selected, installed and re-measured
  - ➔ Iterate as necessary: identify and replace ball/nests with unexpected apex heights
- Grid will be thoroughly surveyed under various conditions: verify/confirm detailed finite element analysis of various flavors performed in advance
  - Room temperature, unloaded
  - Room temperature, loaded (pulled on, etc)
  - Room temperature, under vacuum, unloaded
  - Operating temperature, under vacuum, loaded, pulled on etc.

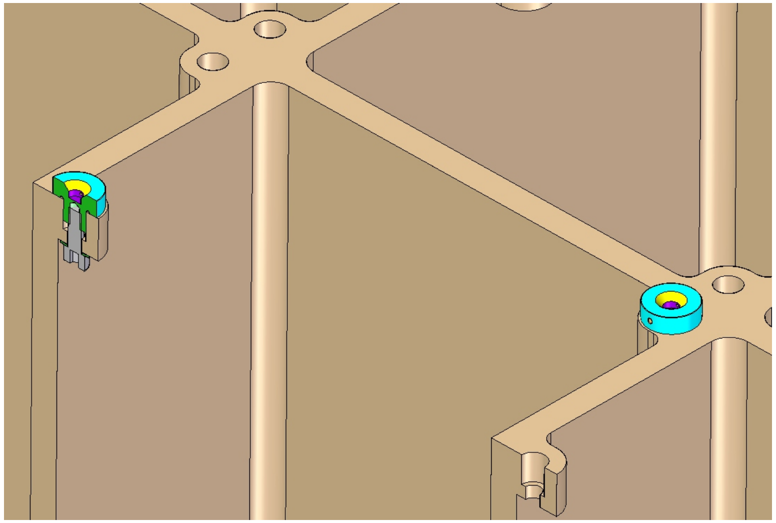
**** not necessarily at room temperature**

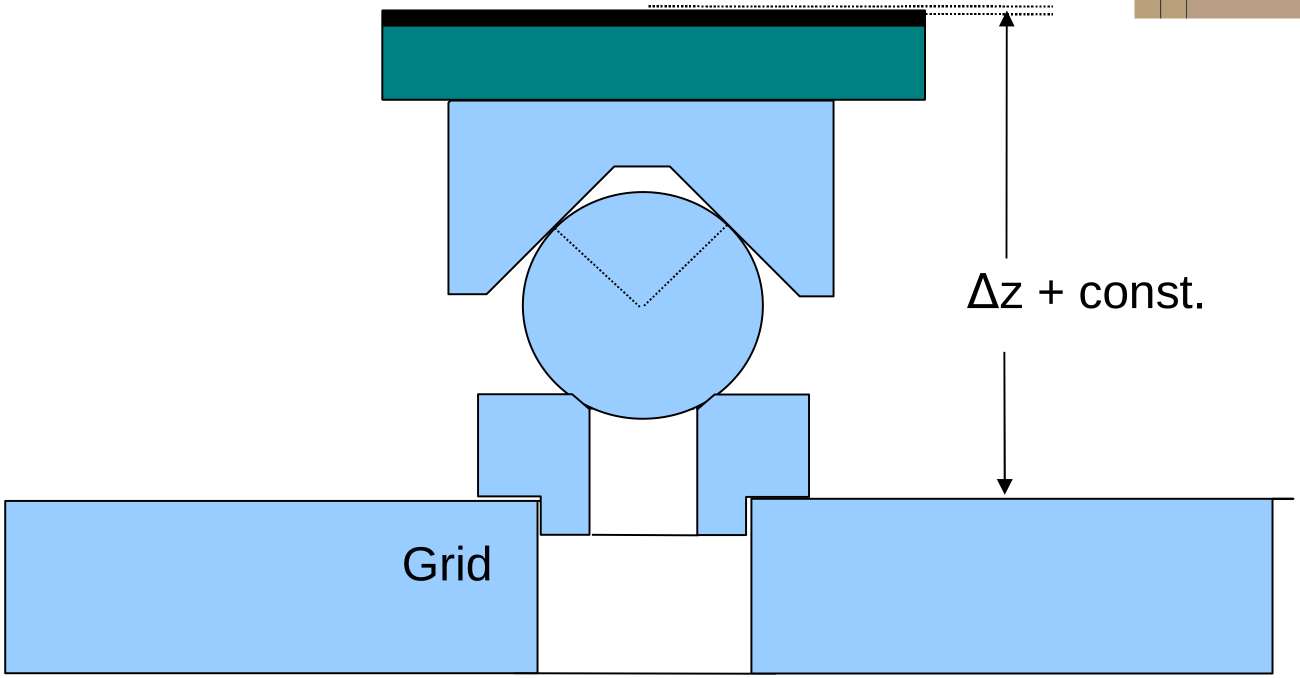
A ball/nest calibration setup:



A better ball/nest calibration setup may contain 3 loaded ball/nests and a double sized optical flat with (measured) wedge value. Three ball/nest heights may be obtained in a single configuration.

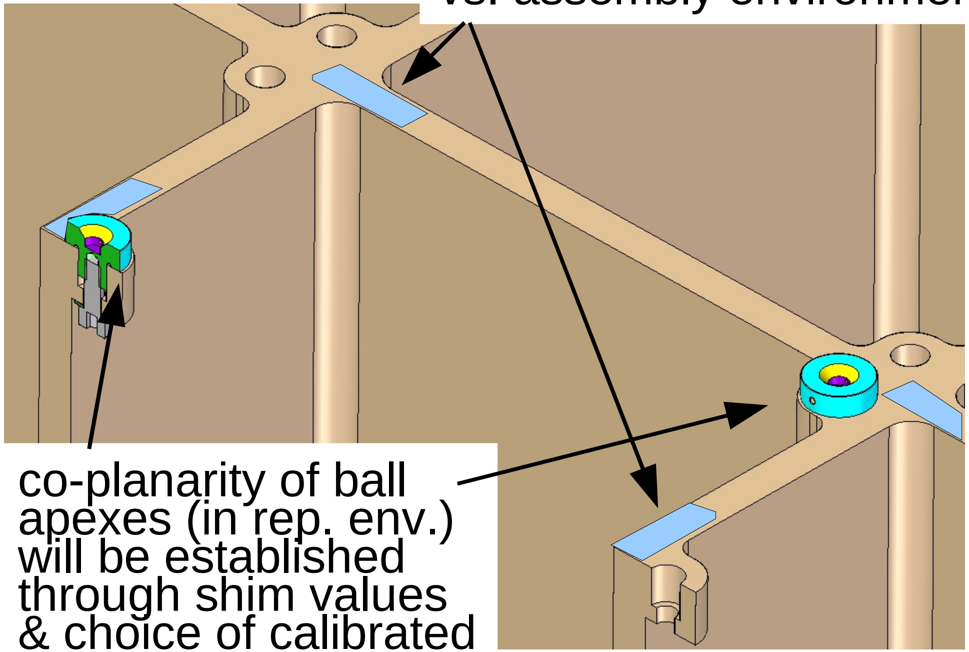
Choosing the right ball/nest in the grid is possible once Δz is known for that location





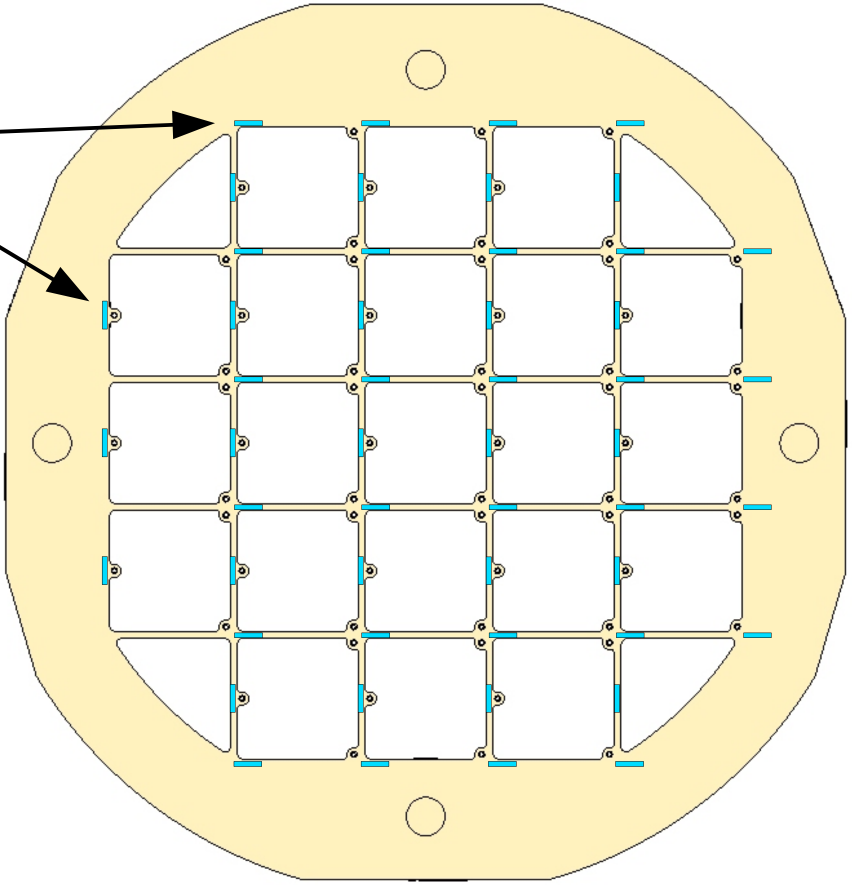
Assign ball/cup shim values across FP grid

- Install (& preload) calibrated ball nests into grid
- Stitch grid: optically flat reference surfaces and ball apexes or optical flat that span balls

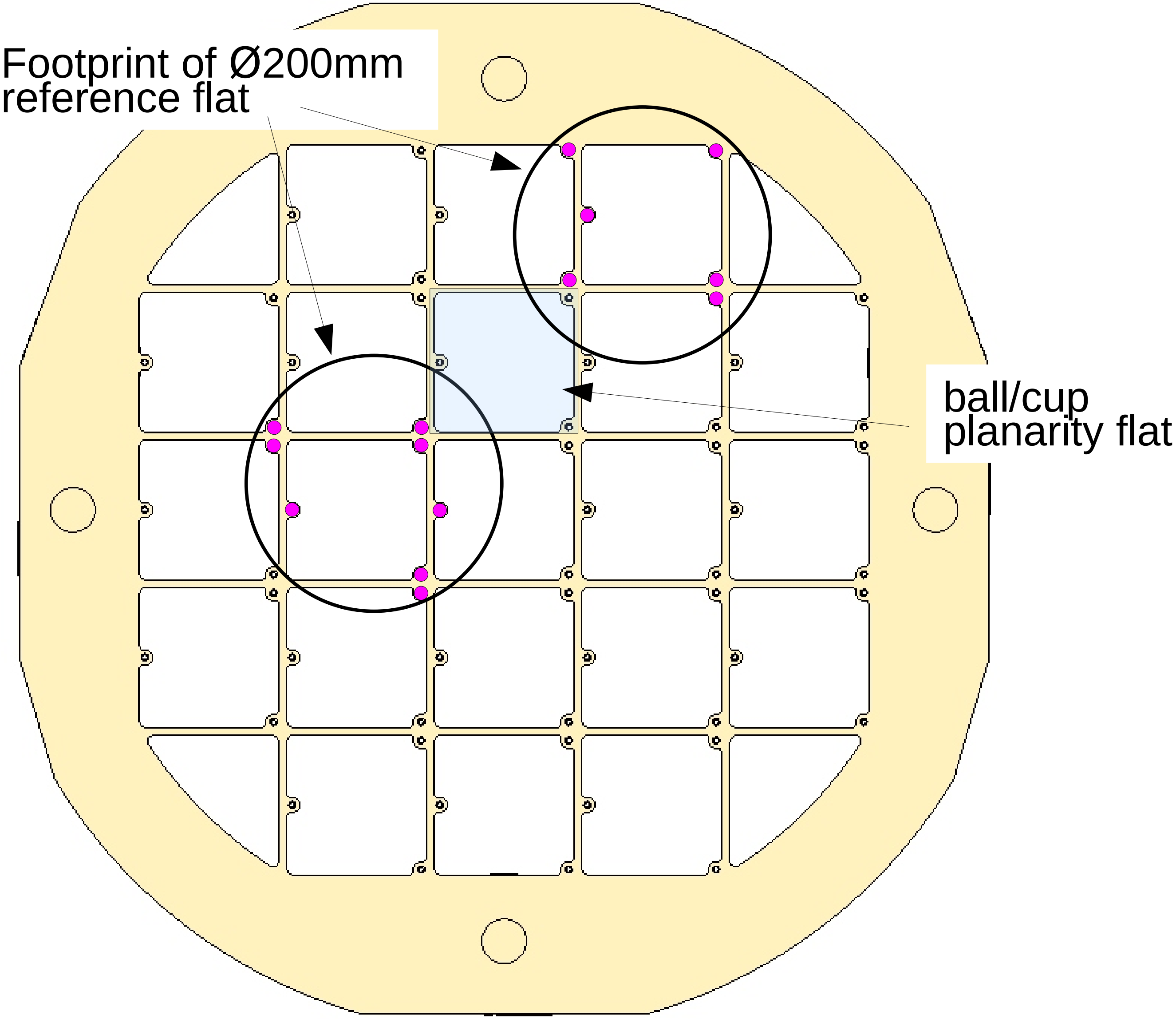


non-contact datum pads (for grid distortion measurements in representative environment vs. assembly environment)

co-planarity of ball apexes (in rep. env.) will be established through shim values & choice of calibrated ball cups

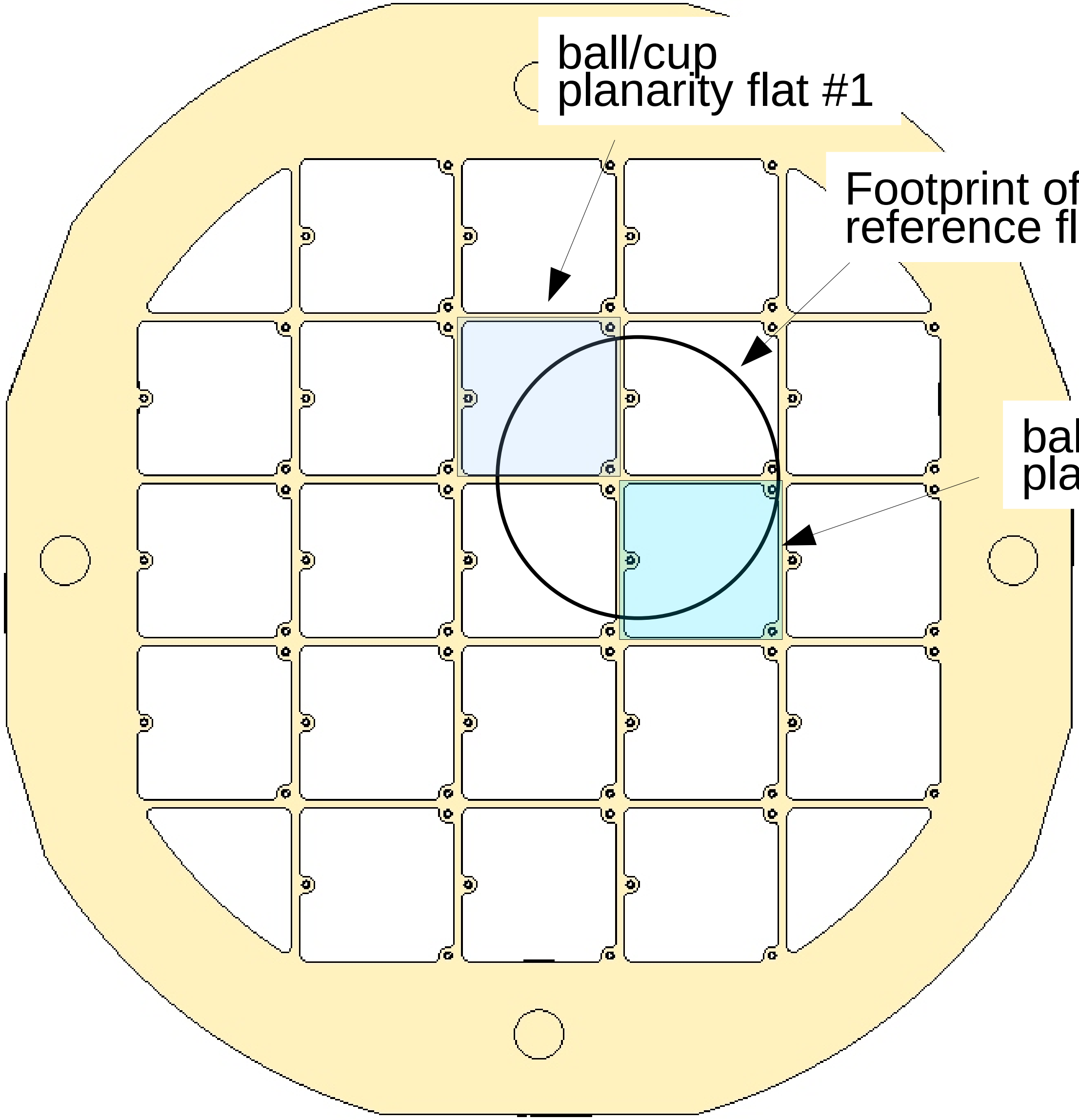


Assign ball/cup shim values across FP grid


Footprint of Ø200mm reference flat

ball/cup planarity flat

Assign ball/cup shim values across FP grid

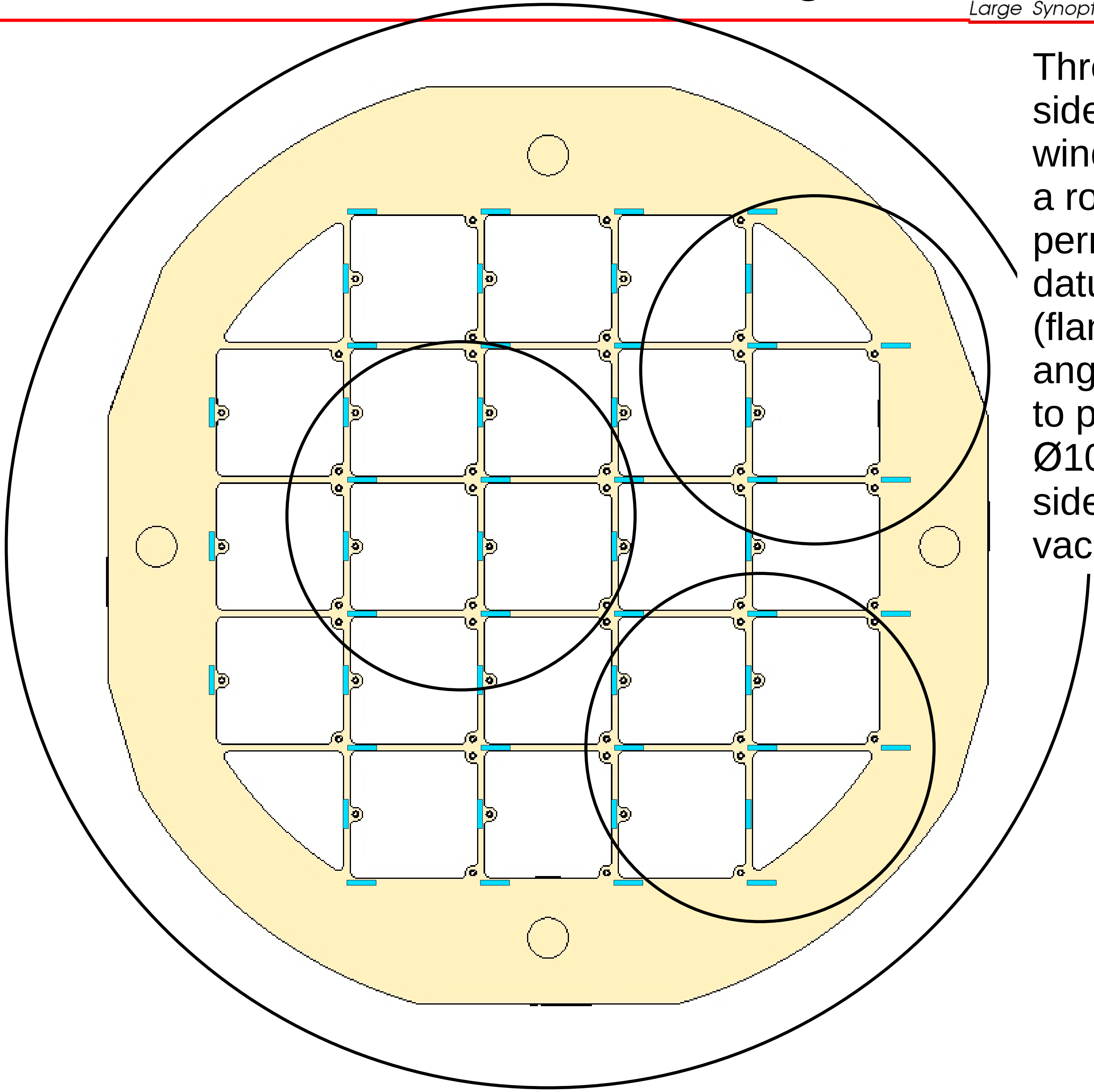


ball/cup
planarity flat #1

Footprint of Ø200mm
reference flat

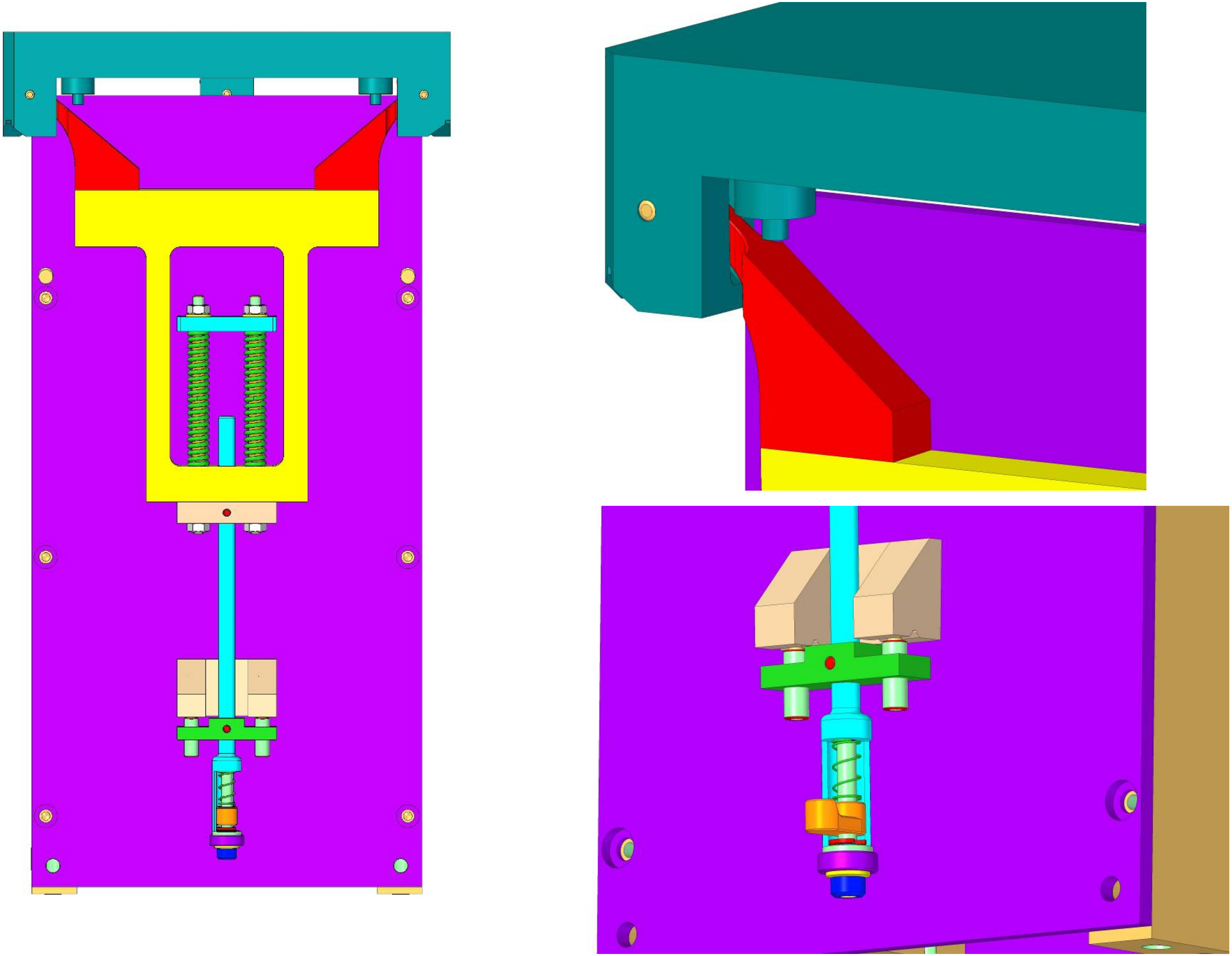
ball/cup
planarity flat #2

Environmental distortion across FP grid

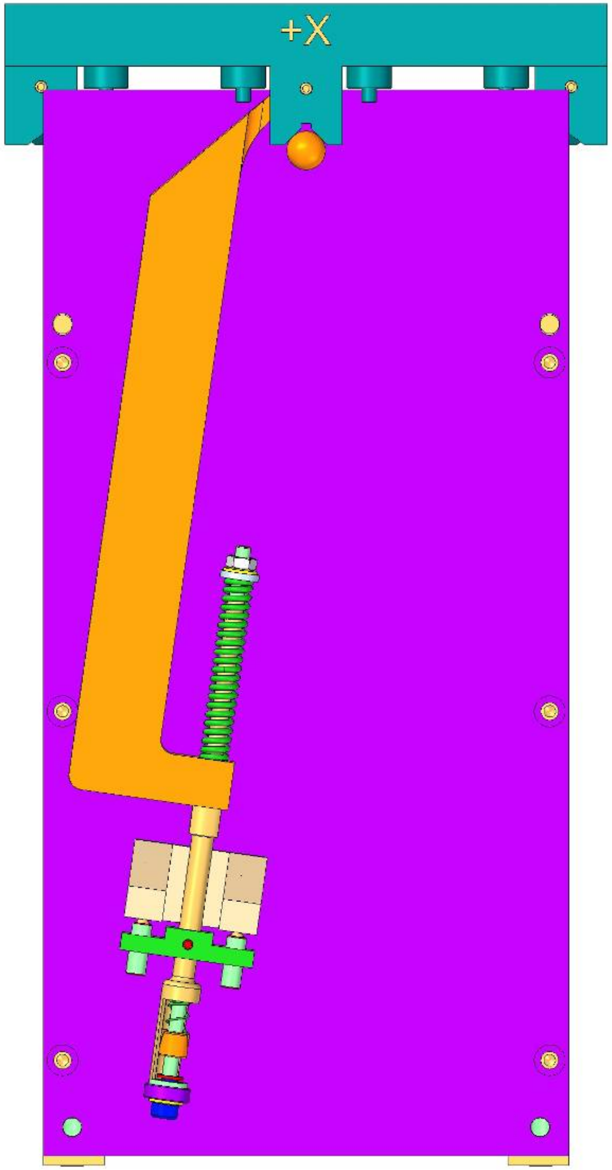


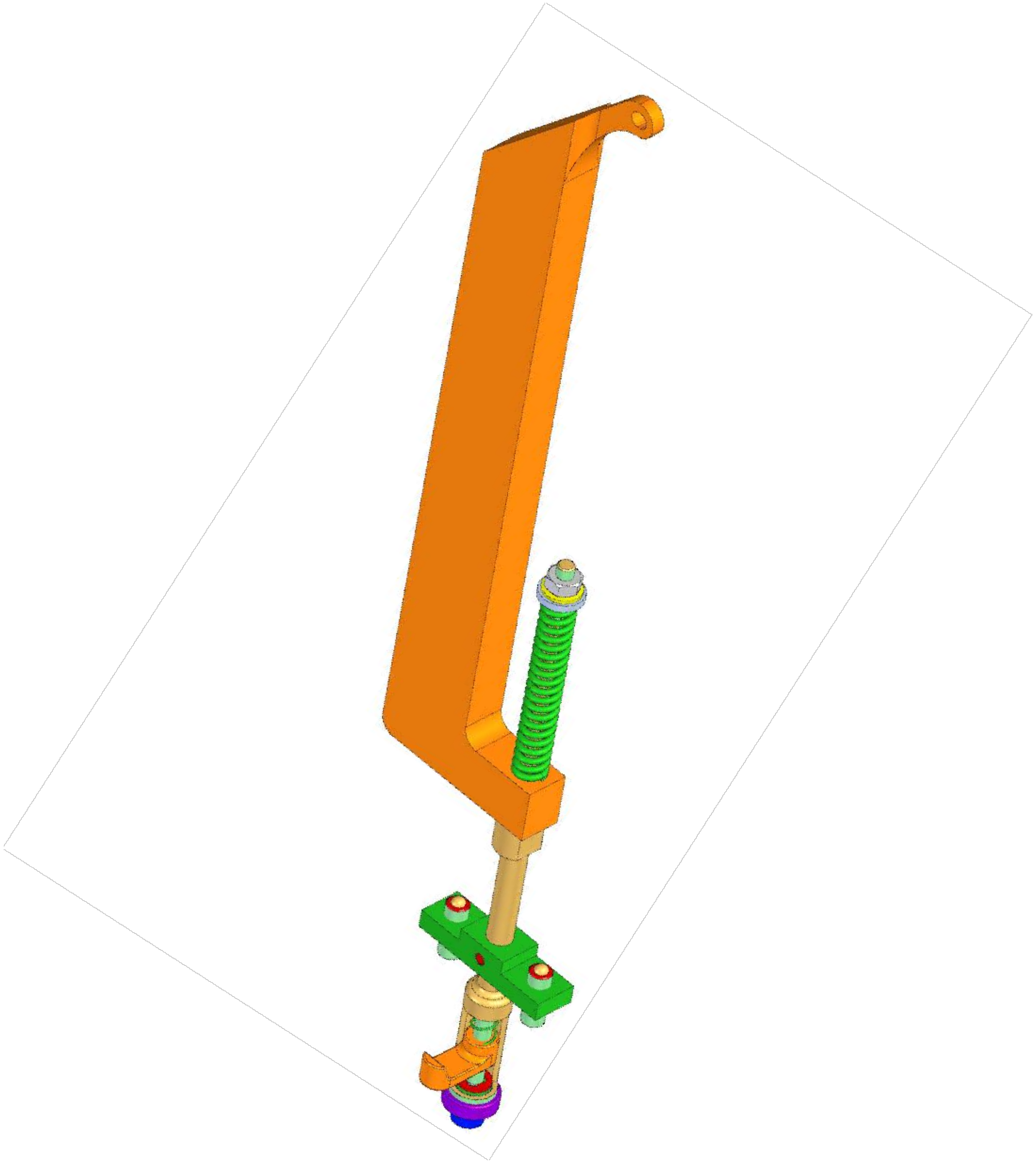
Three 12” OD double sided optical flat windows off-center on a rotatable flange will permit full sampling of datum pads in several (flange) clocking angles. (an alternative to producing a Ø1000mm double sided optical flat vacuum barrier.

-X Side Raft Hold-Down

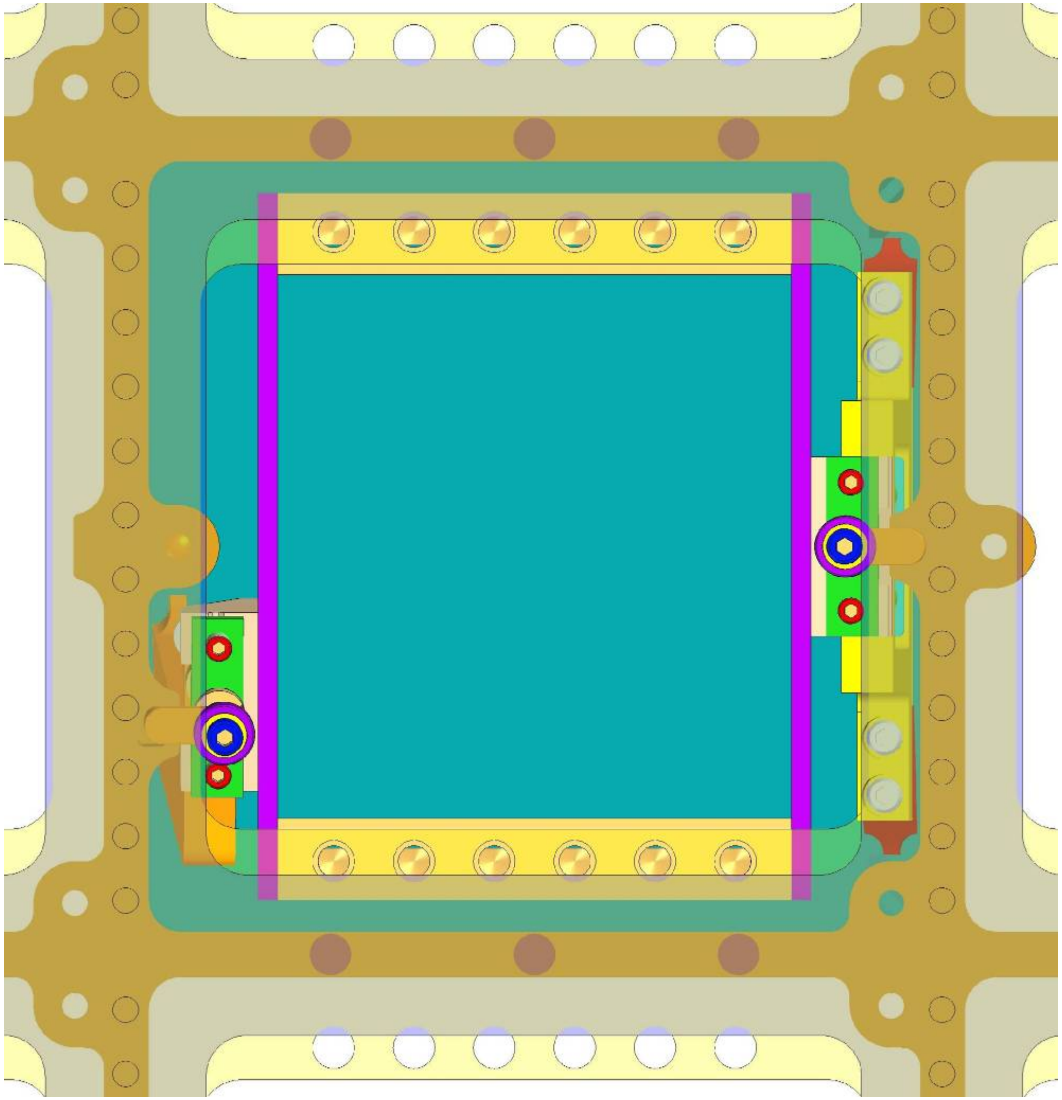


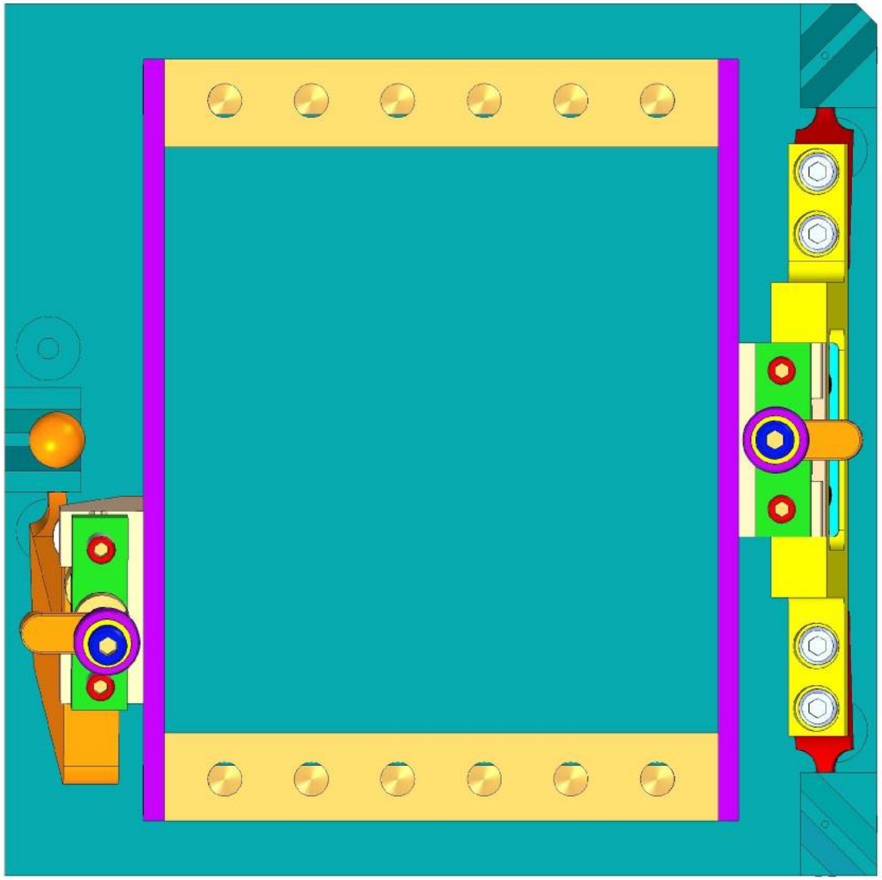
+X Side Raft Hold-Down



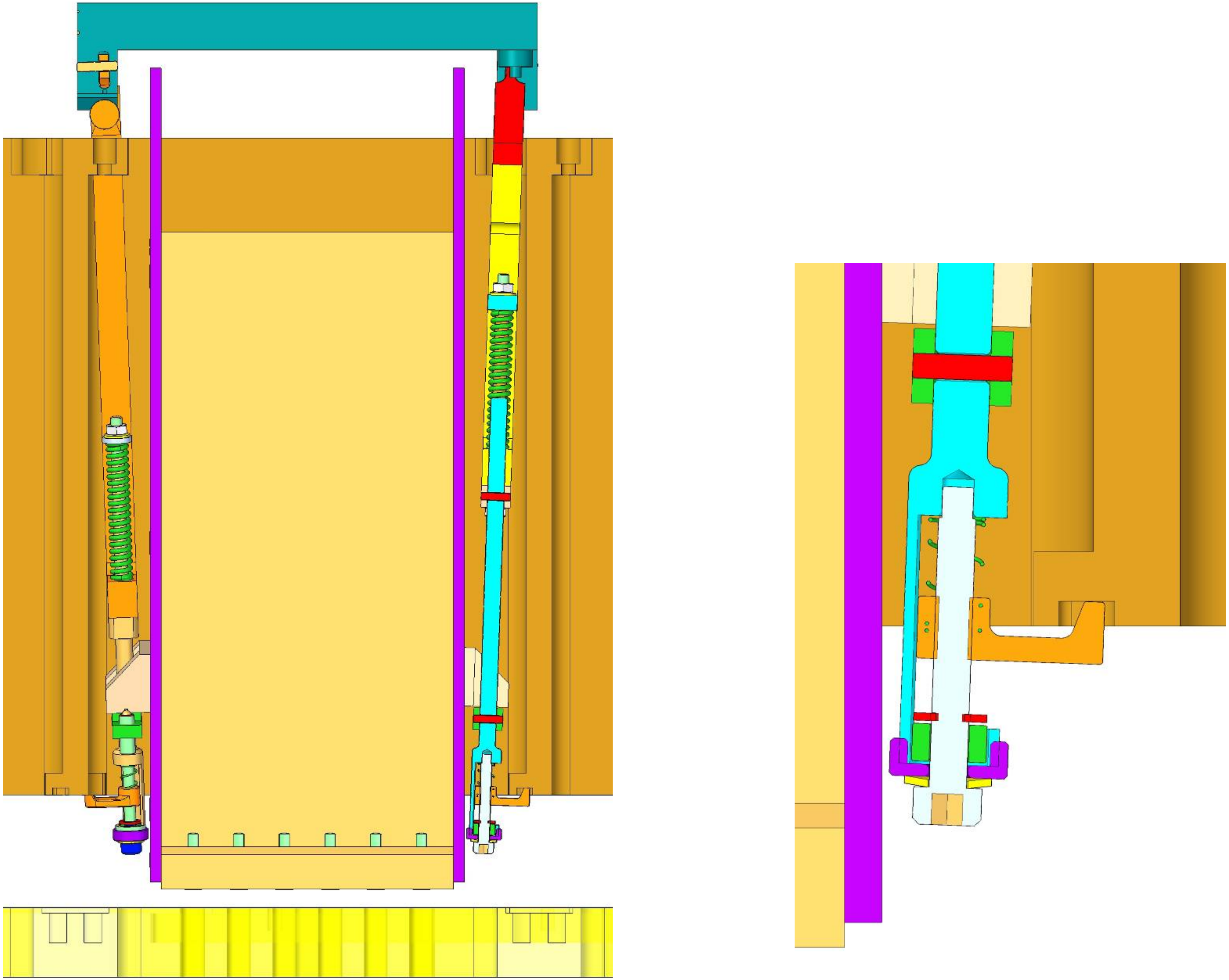


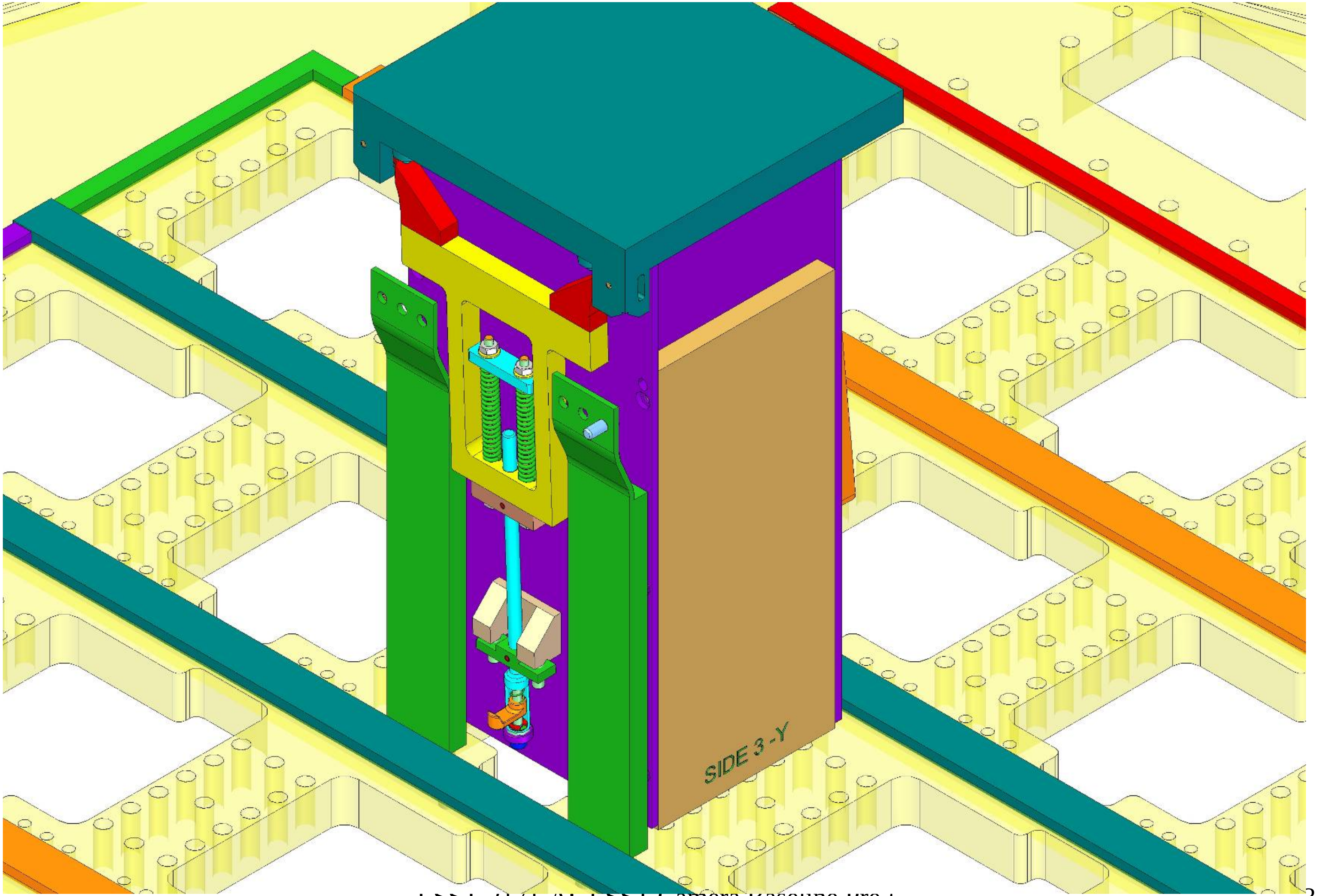
Back End Views



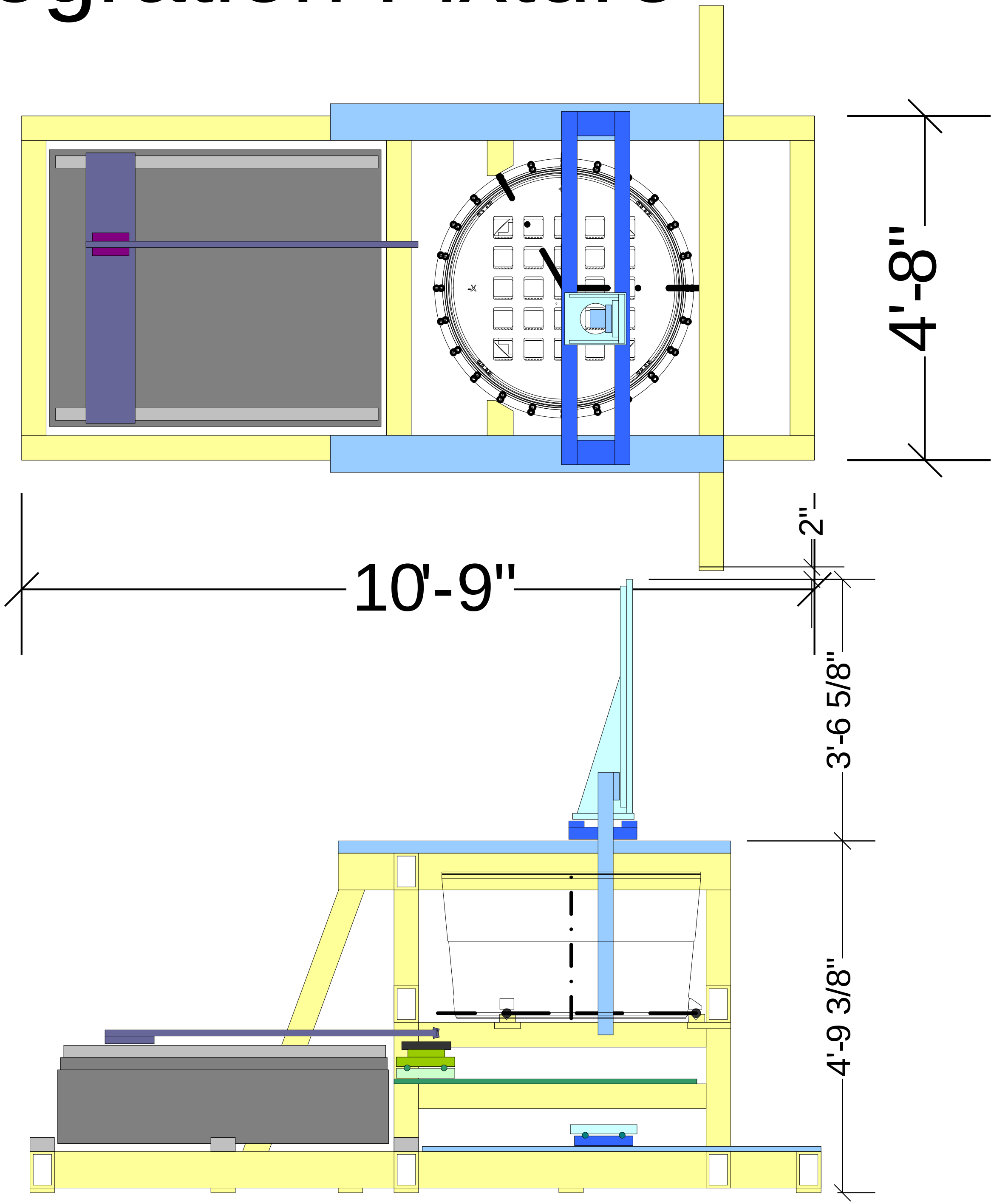


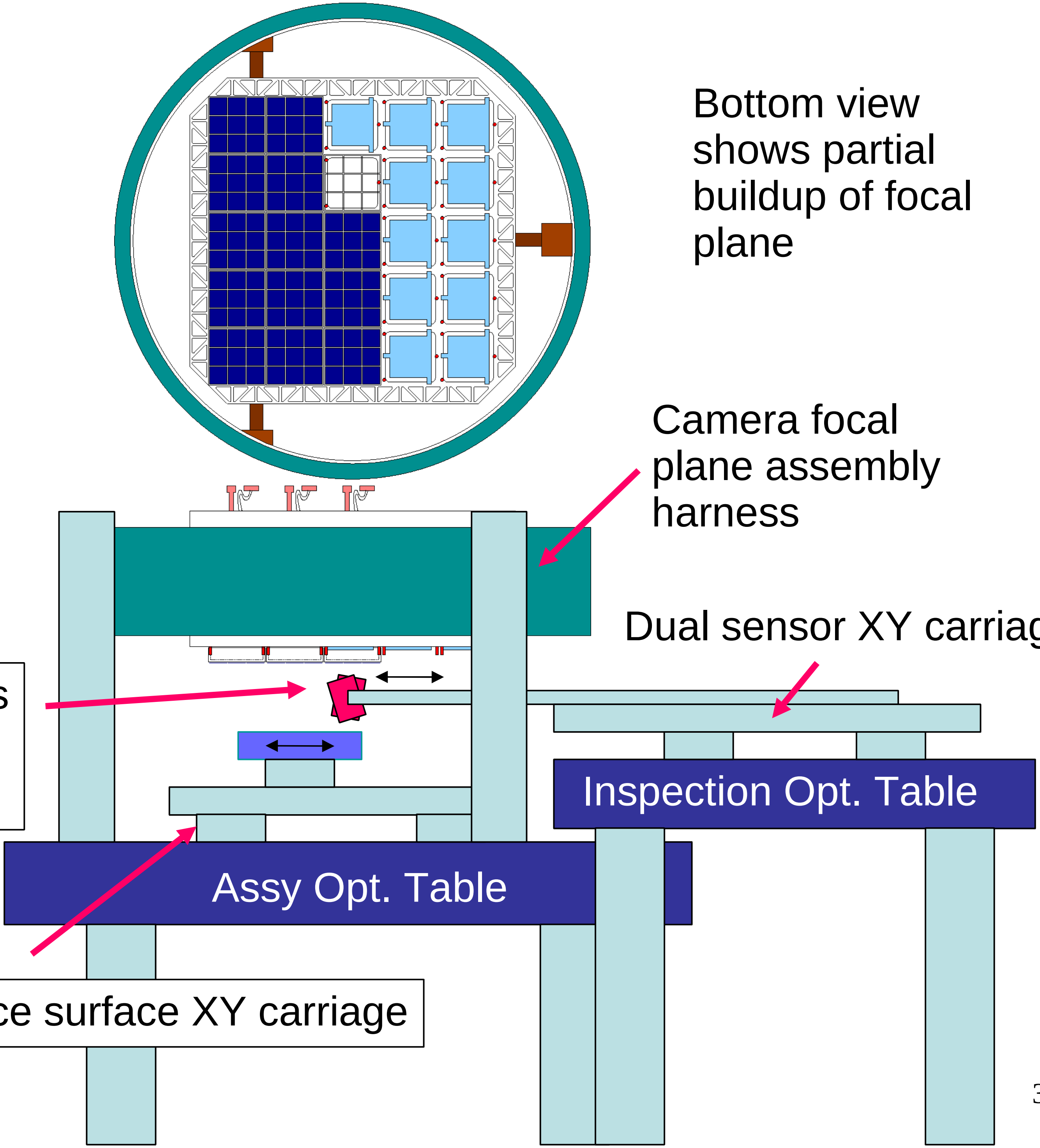
Y-Direction Side Section




SIDE 3 -Y

Cryostat Integration Fixture





Bottom view shows partial buildup of focal plane

Camera focal plane assembly harness

Dual sensor XY carriage

Displacement sensors (up & down looking)

Inspection Opt. Table

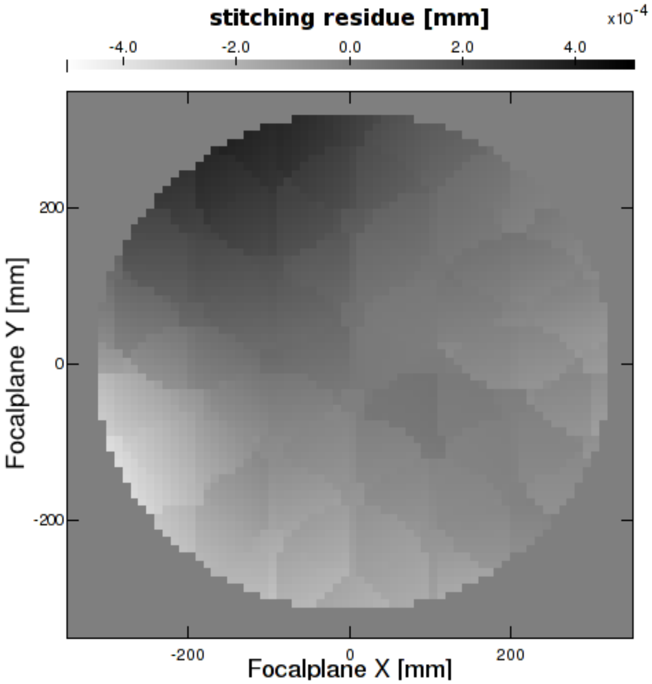
Assy Opt. Table

Reference surface XY carriage

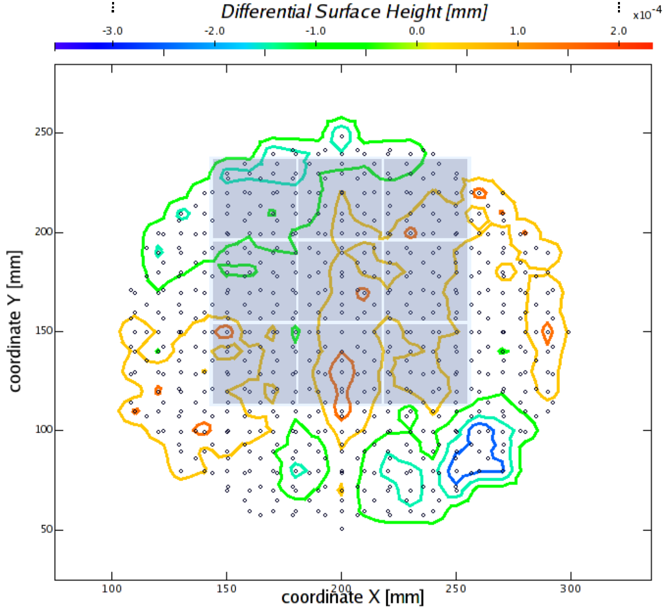
Stitching for FP Metrology

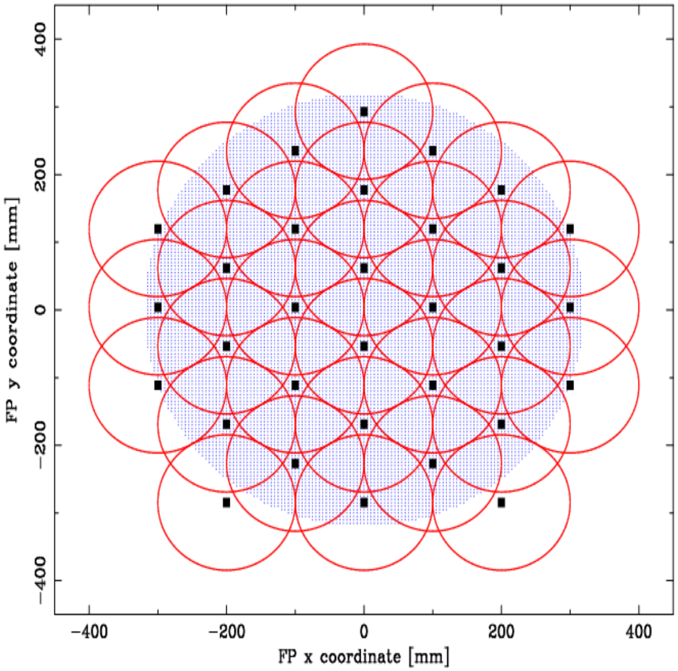
- Combine multiple, rapidly acquired measurements using arbitrary (but stable) reference flats

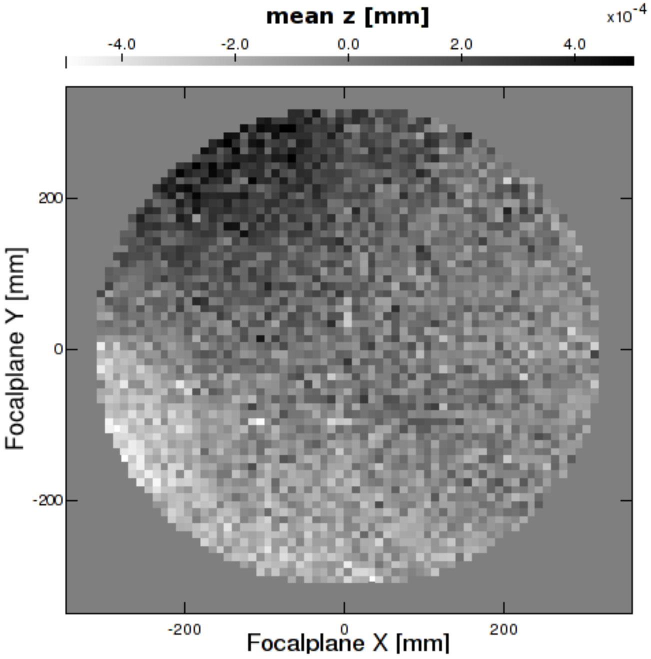
[Rasmussen et al. Proc. SPIE, Vol. 6273, 62732U (2006)]



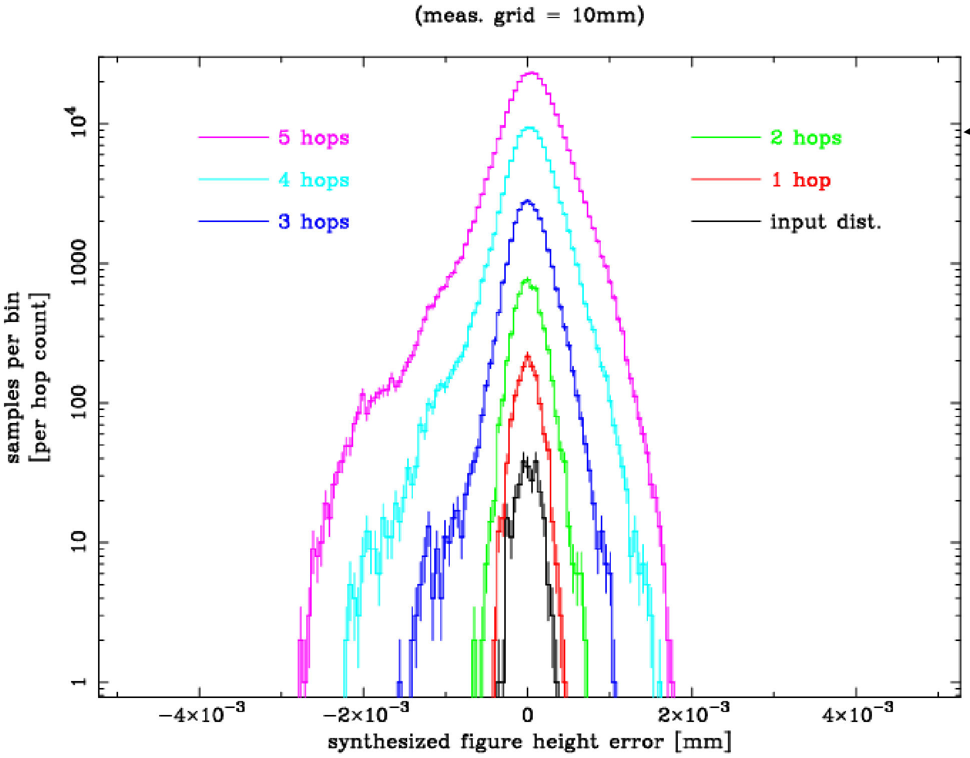
Current systematic limit: 5% of P-V requirement





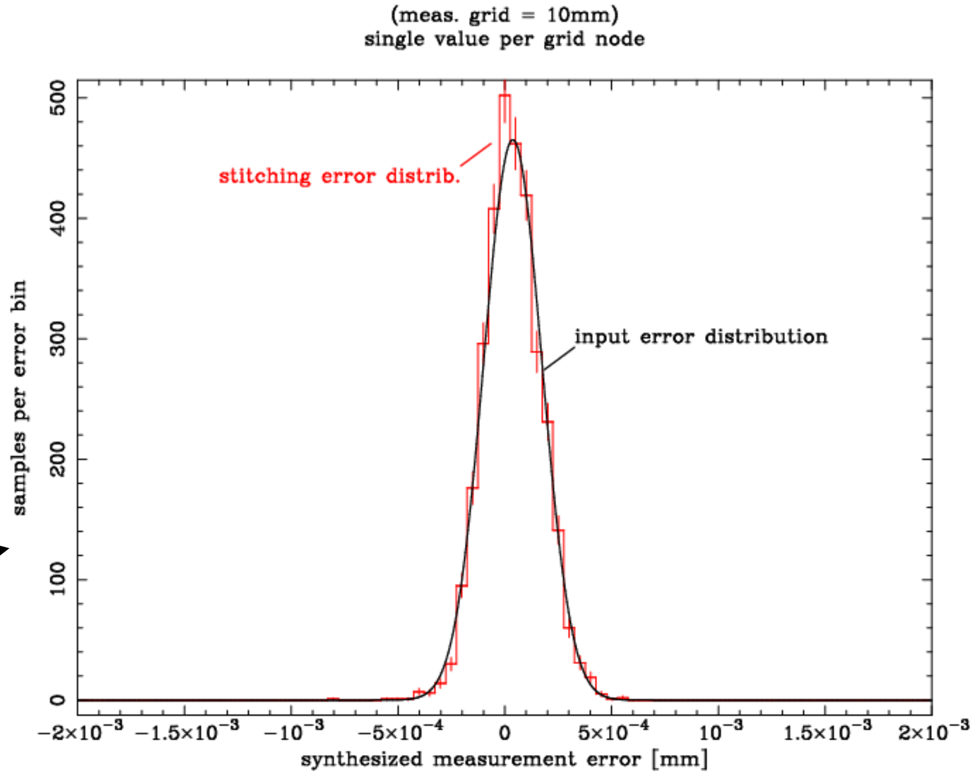


Stitching algorithm, using apparent differential metrology error distribution



Error degradation with increased intermediate references (“hops”)

Single value per measurement grid node (average available computations):
Input error distribution nearly recovered.



=> Should work fine for measuring environmental grid distortion and initial ball arrangement

Raft-Grid Interface & Metrology

P.O'Connor [BNL], A.Rasmussen [SLAC]

- **Kinematic coupling (KC) prototype results:**
  - **a) repeatability, measurement precision**
  - **b) Material options: raft vee - block and grid ball materials and coatings**
  - **c) Plan for testing**
- **Metrological transfer of RAFT to GRID:**
  - **a) GRID preparation**
  - **b) Raft Preparation**
  - **c) Pre-load load transfer: design update to transfer pre-load to grid**
  - **d) Master tooling and raft support during ass'y and test:**
  - **e) Concept for tooling through the process**
- **Metrology Requirements During Raft and Cryostat I&T :**
  - **a) Requirements for testing for flatness of rafts and GRID during all phases (eg: assembly of rafts and integration into GRID)**
    - **i. warm**
    - **ii. cold**
    - **iii. warm at angles**
    - **iv. cold at angles**
  - **b) Methodology for testing for flatness of rafts and GRID during all phases (eg: assembly of rafts and integration into GRID)**

Raft-Grid Interface & Metrology

P.O'Connor [BNL], A.Rasmussen [SLAC]

- Sensor vendors are to provide sensors with controlled flatness (at ambient)
- Additional shimming will be necessary to produce rafts that are (1) flat and (2) within a 6.5µm wide band, centered at distance [TBD], parallel to the plane formed by apexes of precision balls of the KM mate
- BNL to measure surface height map z(x,y) for assembled raft, warm and cold
- SLAC to confirm surface height map z(x,y) for warm raft
- SLAC to install warm raft into GRID, aiming for desired z(x,y) that features various distortion functions – this is done by choosing appropriate ball/cup heights
- Metrology facility will be used to rapidly verify expected surface height map z(x,y) for newly installed raft
- take appropriate action if measurements are not within expectation: disassemble and reinstall using alternate calibrated ball/cups
- Repeat for next raft, etc.
- Metrology of the assembled FP will be repeated inside the evacuated Cryostat using L3 as the vacuum barrier. Repeat cold to verify flatness under representative environment
- Changes in gravity load will be simulated at various stages by using dummy masses, also by pulling on the GRID in a distributed fashion.

- **Metrology Requirements During Raft and Cryostat I&T :**
  - **a) Requirements for testing for flatness of rafts and GRID during all phases (eg: assembly of rafts and integration into GRID)**
    - **i. warm**
    - **ii. cold**
    - **iii. warm at angles**
    - **iv. cold at angles**
  - **b) Methodology for testing for flatness of rafts and GRID during all phases (eg: assembly of rafts and integration into GRID)**