

The mechanics of ultra-transparent silicon.

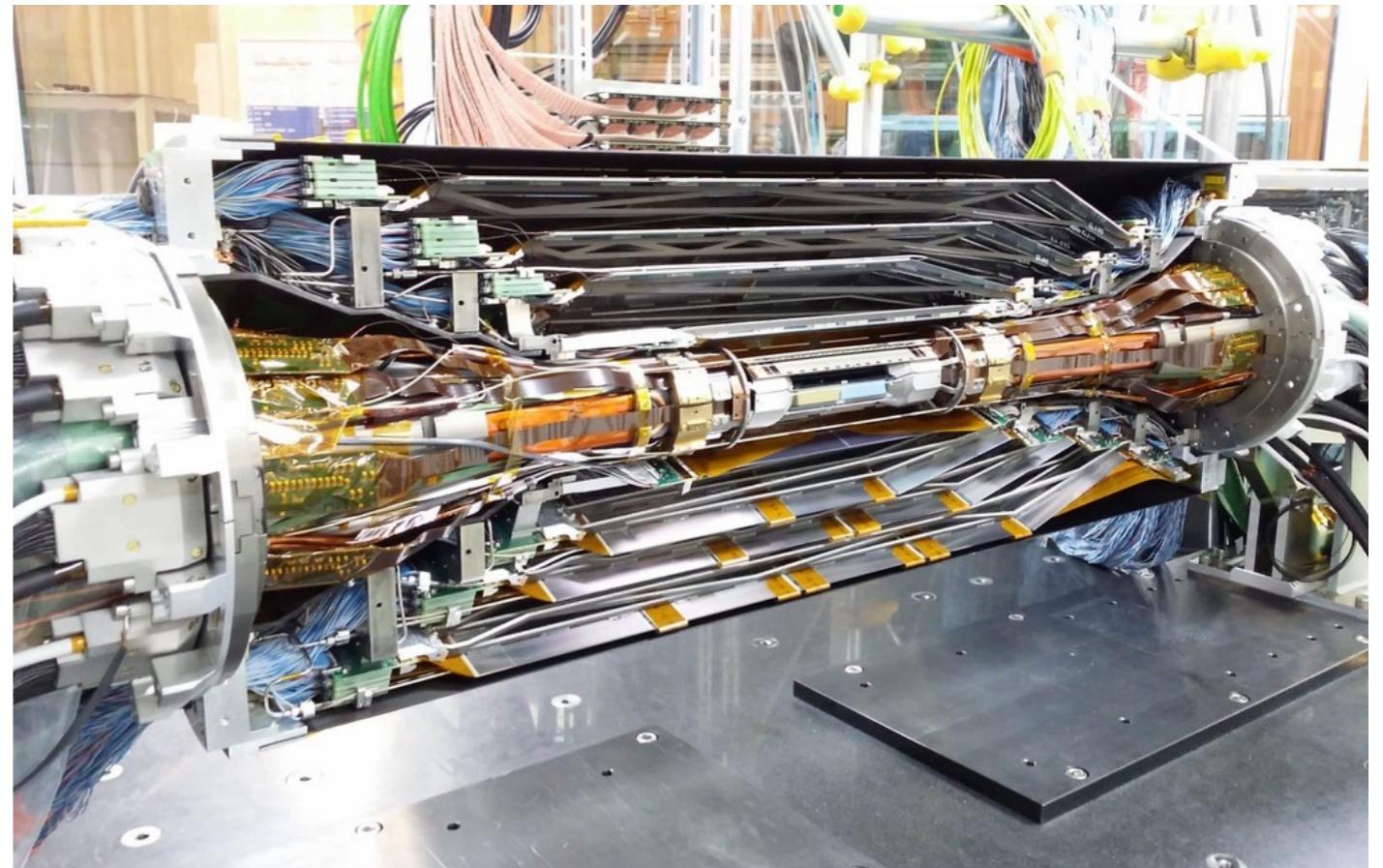
**CLIC det. & phys workshop
CERN, August 2019**

*Miguel Angel Villarejo, Guillem Vidal, Martín Perelló,
Marcel Vos , IFIC (U. Valencia/CSIC), Spain
Laci Andricek (MPG/HLL), Malte Frövel, Maria de la Torre (INTA)
Carlos Marinas (U. Bonn), David Moyá, Ivan Vila (IFCA),
Georg Viehhauser (Oxford)*



Objectives

After much R&D, next-generation pixel sensors (DEPFET, CMOS) can be made extremely thin



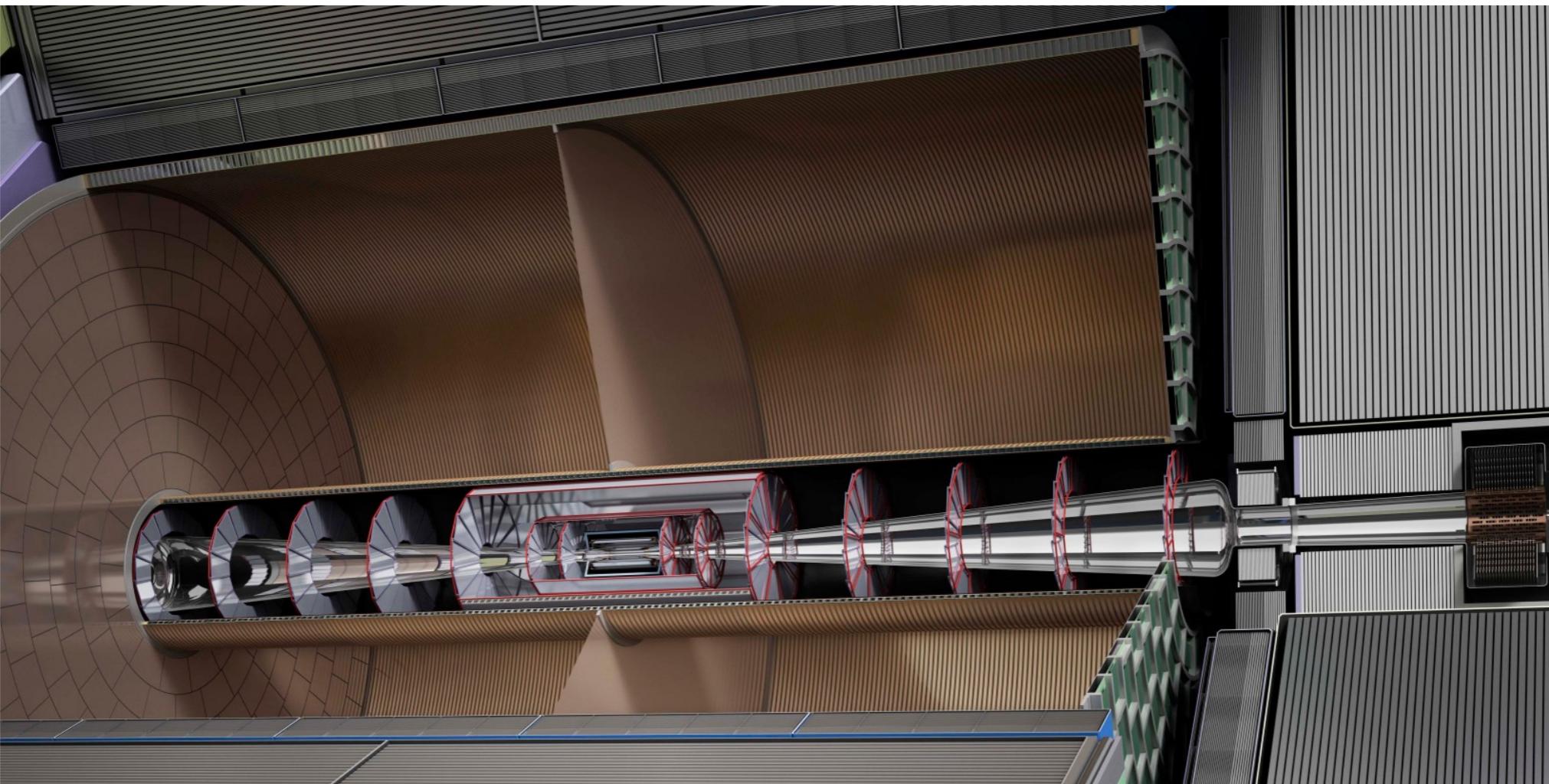
A similar effort on supports & services is required to achieve the material budget!!
---- power pulsing, air cooling, but keep mechanical integrity and position to $O(\mu\text{m})$

This talk: develop complete solution for one sub-system: ILD Forward Tracker Disks

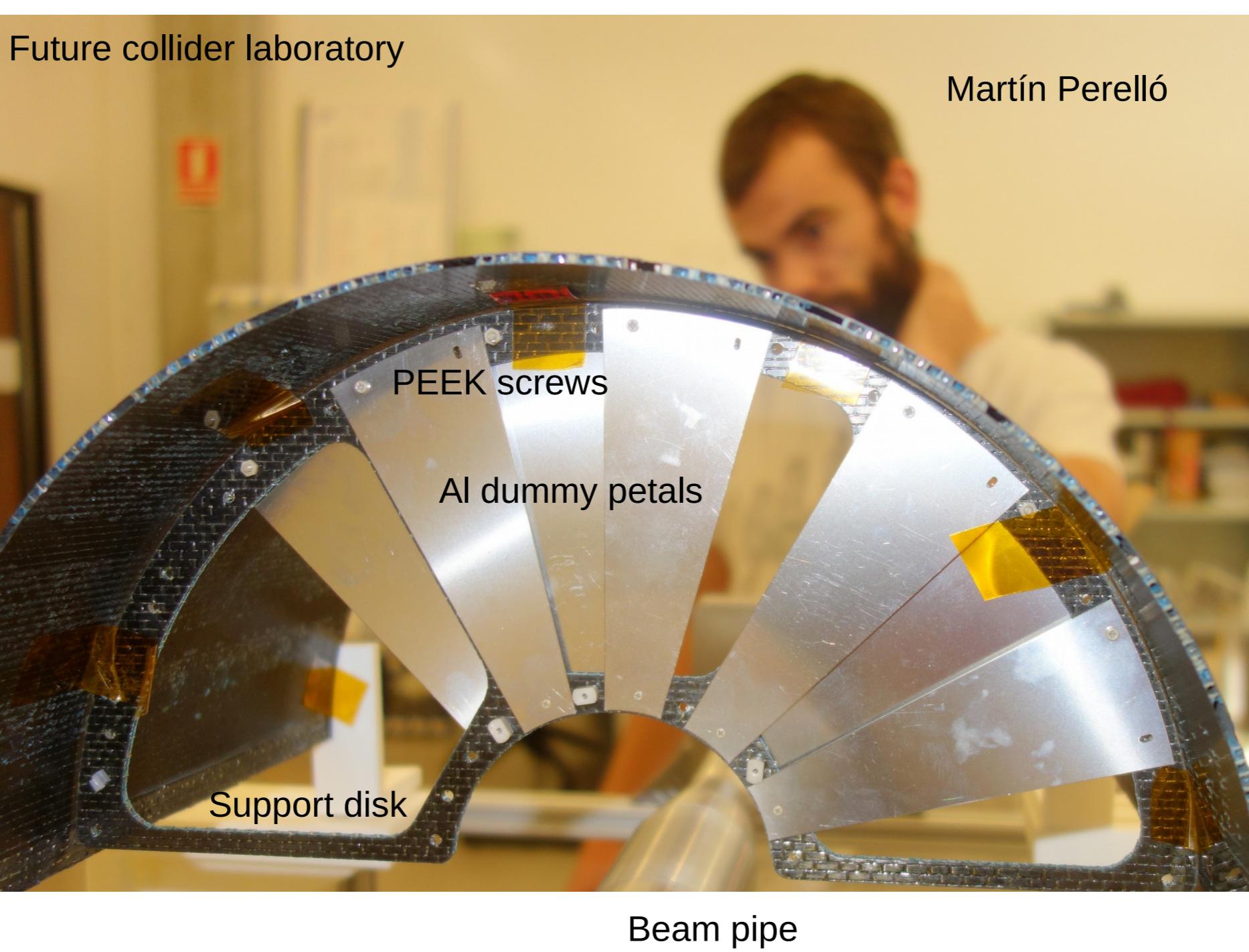


The ILD tracker and FTD

- Mixed silicon (vertex, FTD, SIT, SET) and gaseous system (TPC)
- Seven disks cover the forward region between the TPC and the beam pipe.
- Innermost two disks pixelated single layer of silicon sensors
- Five outer disks equipped with a double layer of strip-based silicon sensors (\rightarrow CMOS?)



The old mock-up



In the long term, the mock-up should develop into a complete system, including beam pipe, support and services, and micro-strip disks under development at IFCA in Santander



A mock-up for the Forward Tracking Disks

Dimensions reflect ILD design

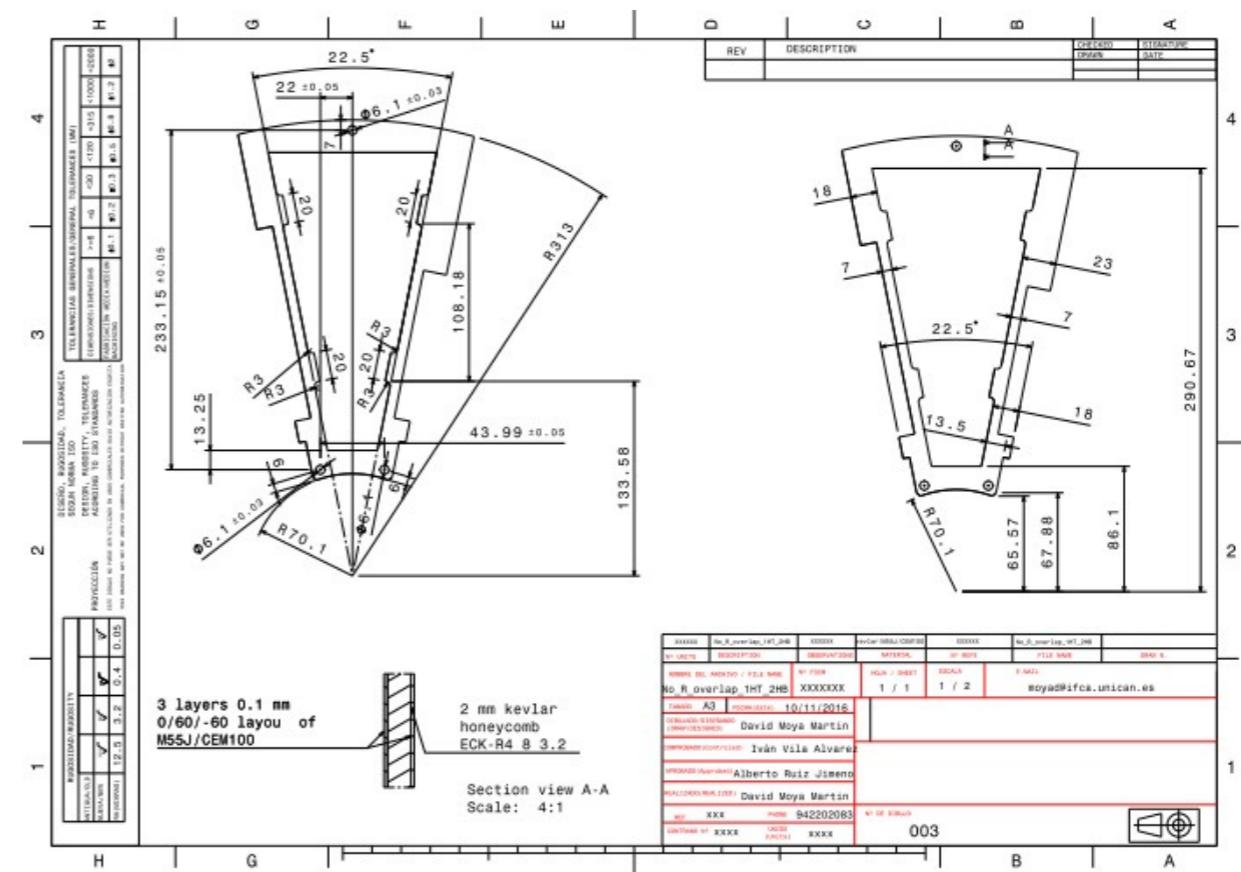
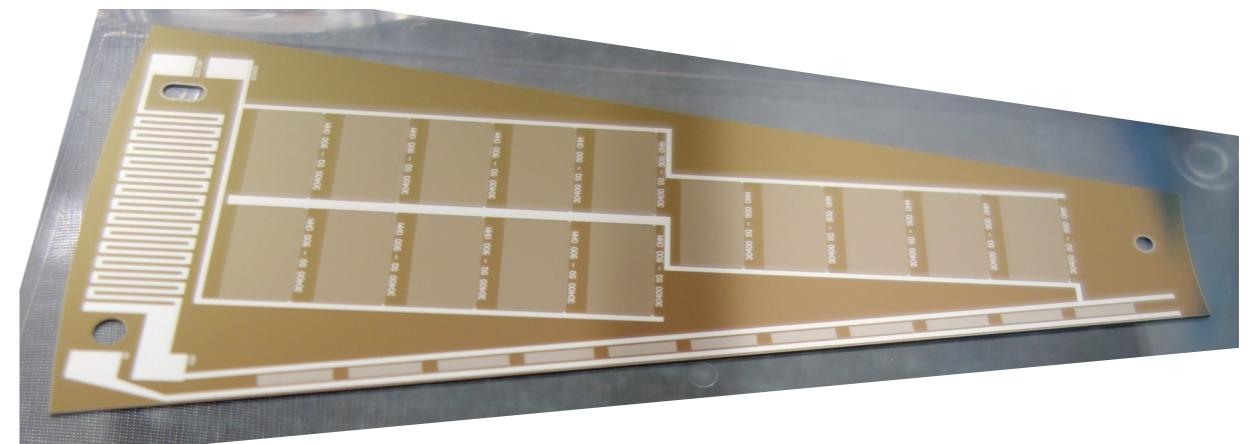
Goal: gain hands-on experience with thermal and mechanical performance of ultra-thin CF+silicon structure

Silicon petal design by Miguel Angel Villarejo (IFIC) in collaboration with Ladislav Andricek (MPG-HLL)

Material budget:

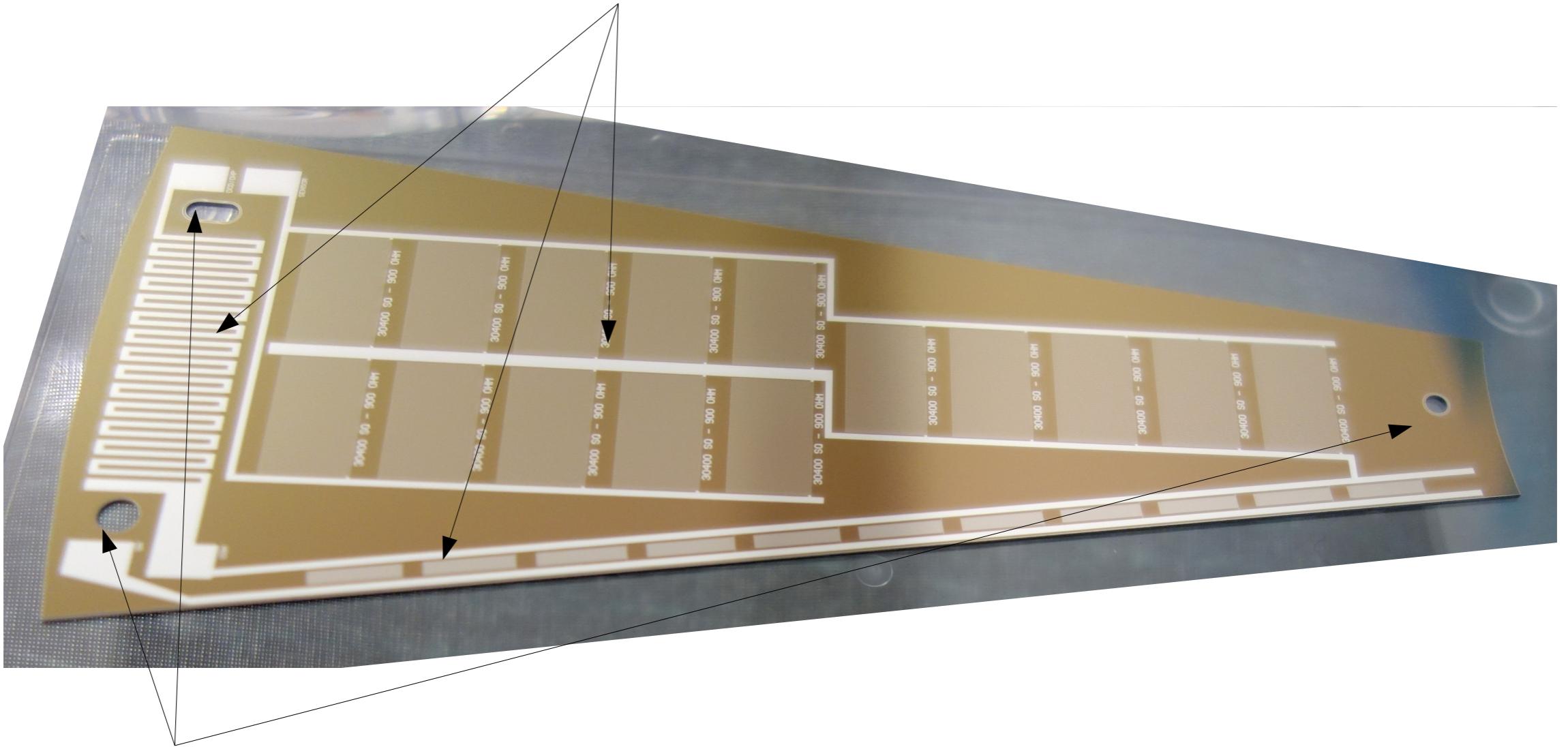
sensor = $50 \mu\text{m}$ Si = 0.05 % X_0

frame = $500 \mu\text{m}$ Si = 0.5 % X_0



A mock-up for the Forward Tracking Disks

Heater circuits on the sensor (single Al metal layer)



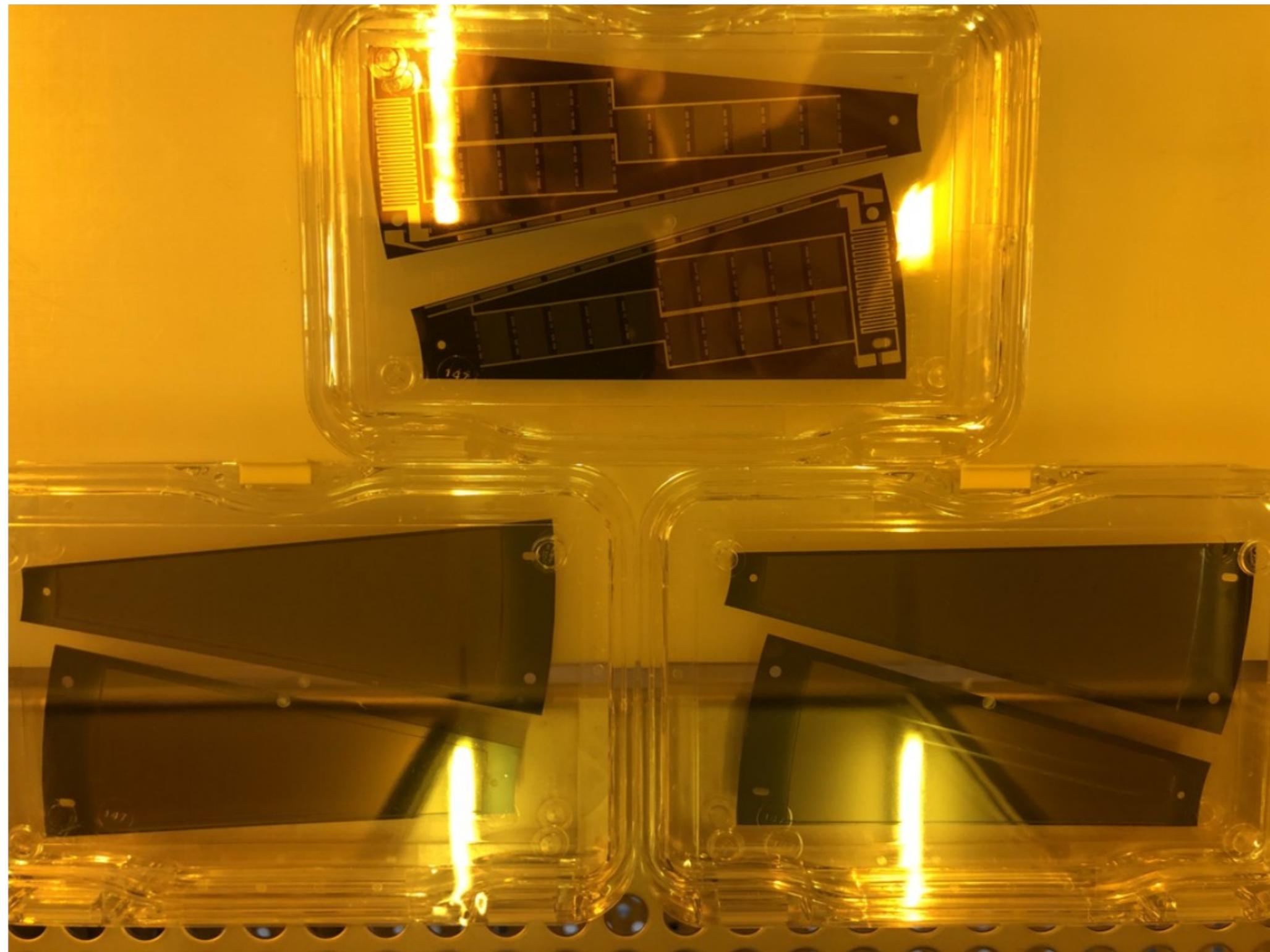
Kinematic mounting slots: when the sensors are mounted with a PEEK screw with a precisely controlled torque, these mountings provide a solid 3D constraint, while leaving the sensor enough freedom for thermal expansion.



All-silicon petals

New production at silicon lab of the Max Planck society in Munich

Petals arrived at IFIC in September 2018 and are currently being mounted on mock-up structure

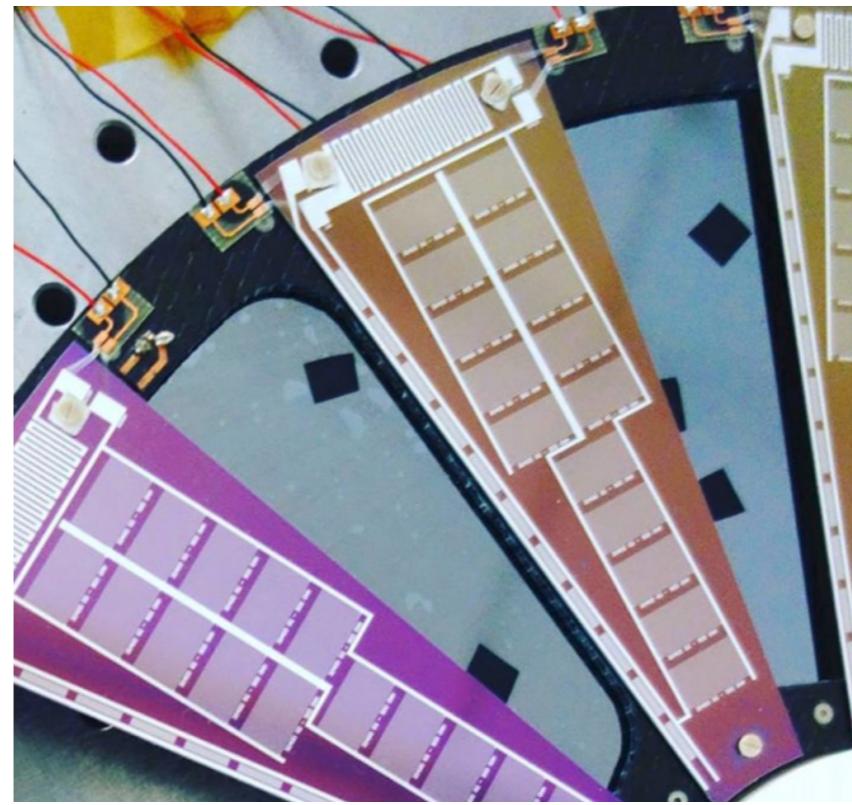


A mock-up for FTD 1 and 2

Dimensions reflect ILD design

Goal: gain hands-on experience with thermal and mechanical performance of ultra-thin CF+silicon structure

Support structure by M.A. Villarejo with Malte Frovel and Maria de la Torre of the composite materials group at INTA in Madrid



Average material budget:

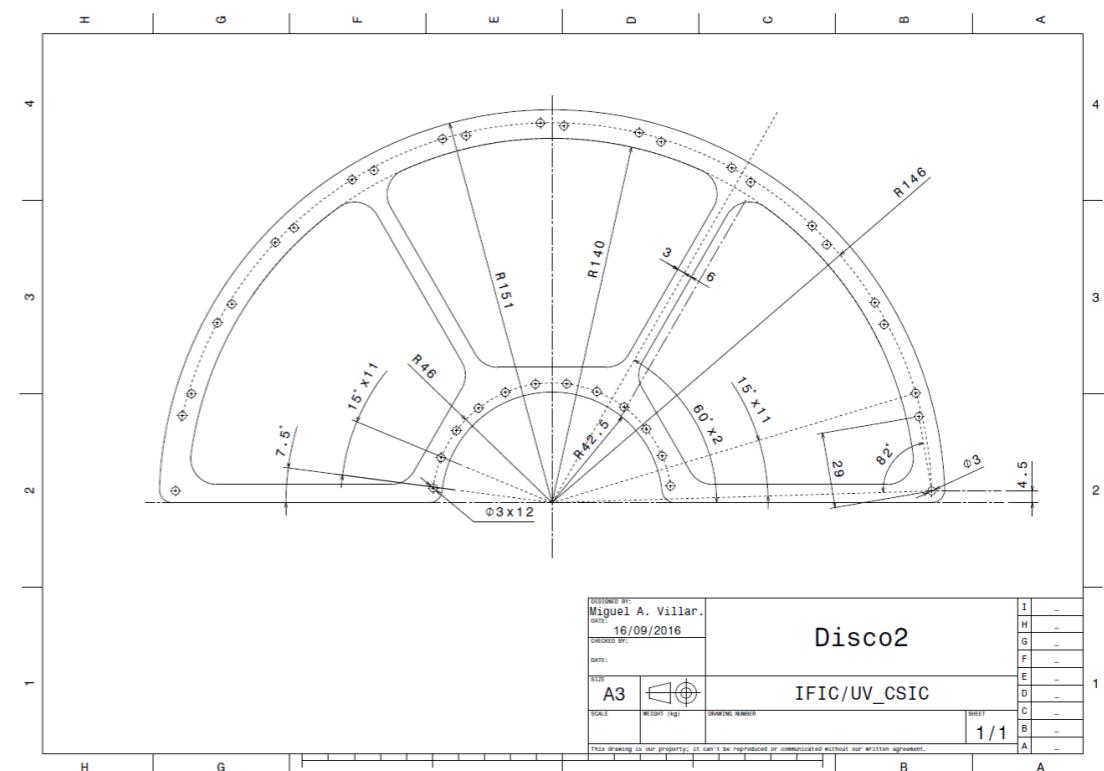
C-fiber: $0.038\% X_0$ (skin + honeycomb)

Epoxy : $0.0006\% X_0$

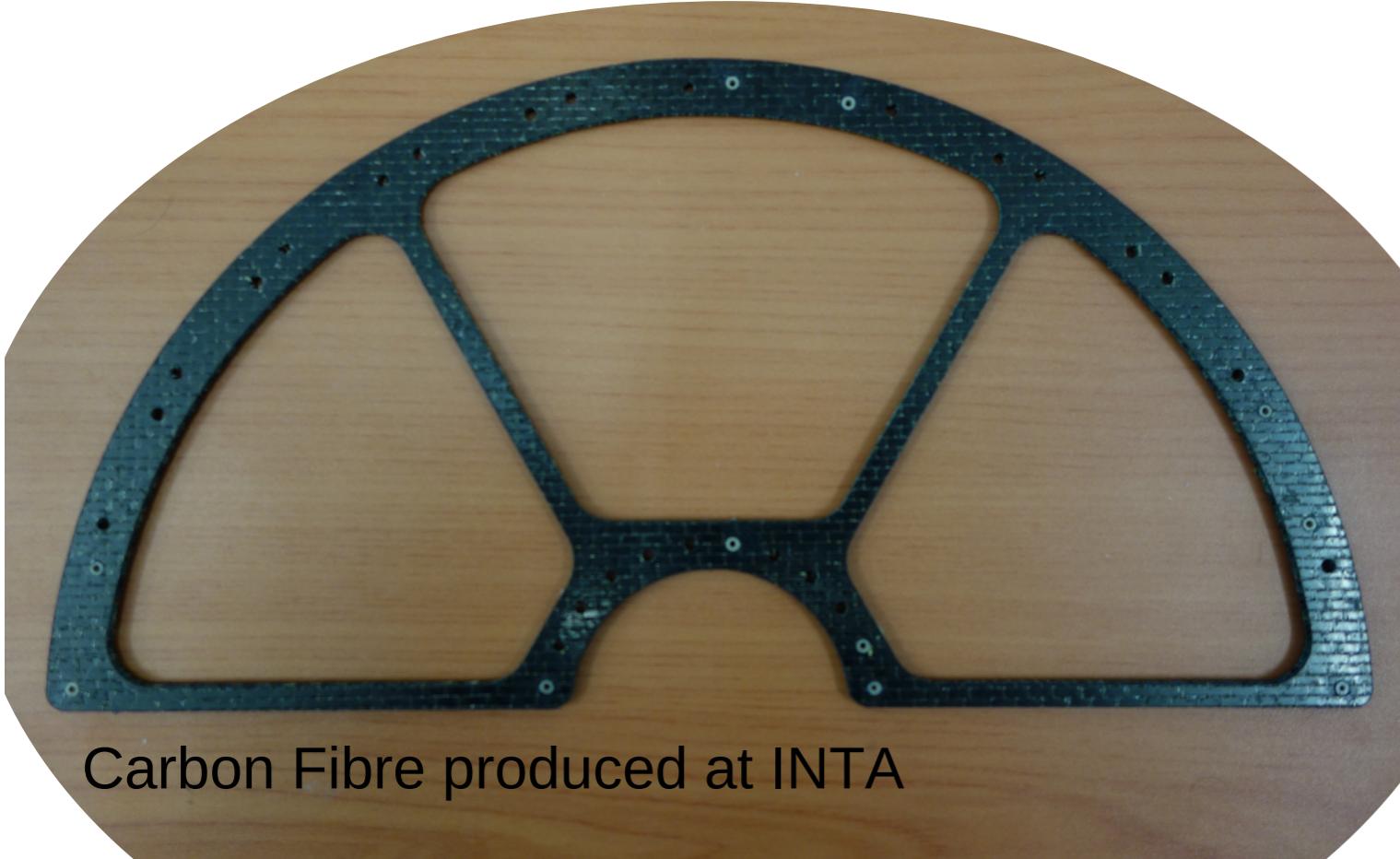
PEEK : $0.0033\% X_0$ (inserts + screws)

Glue : $0.0006\% X_0$

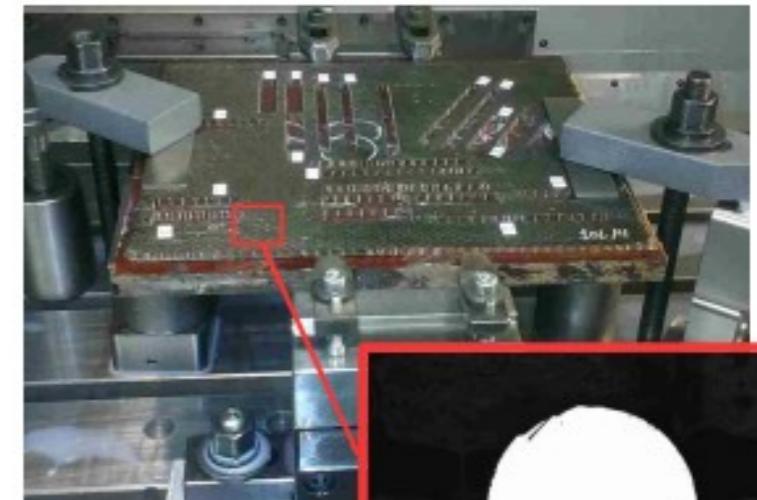
Total : $0.042\% X_0$



Carbon Fibre disk production



Cutting at Ramem (Madrid)



test samples



Material budget

FTD1	
Carbon fiber + cyano-ester resin	0,0376535
Honeycomb (aramide)	0,0006276
Peek inserts	0,0019486
Peek screws	0,0014073
Inserts glue	0,0006495
Total X/X₀ %	0,0422866

Material in % of X_0 , averaged over area

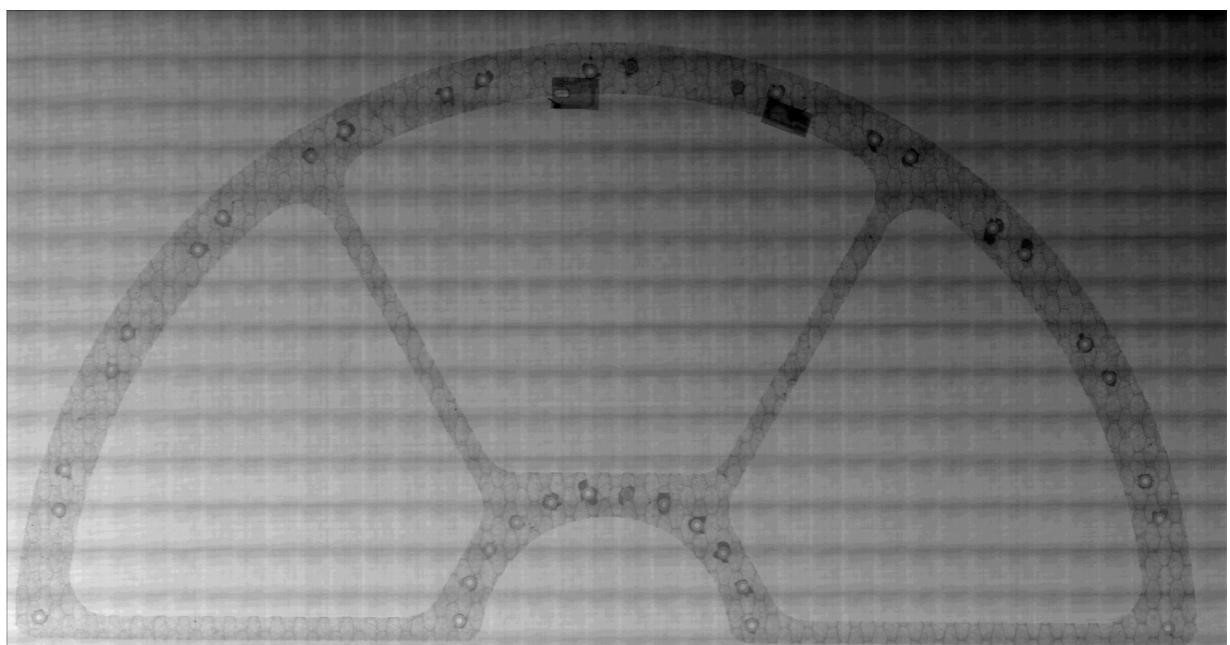
FTD2	
Carbon fiber + cyano-ester resin	0,0383109
Honeycomb (aramide)	0,0006385
Peek inserts	0,0020261
Peek screws	0,0014633
Inserts glue	0,0041013
Total X/X₀ %	0,0465401

Disk contributes less than 0.05% of a radiation length to the material budget

X-ray map of the material in FTD1:



Weight: less than 15 g



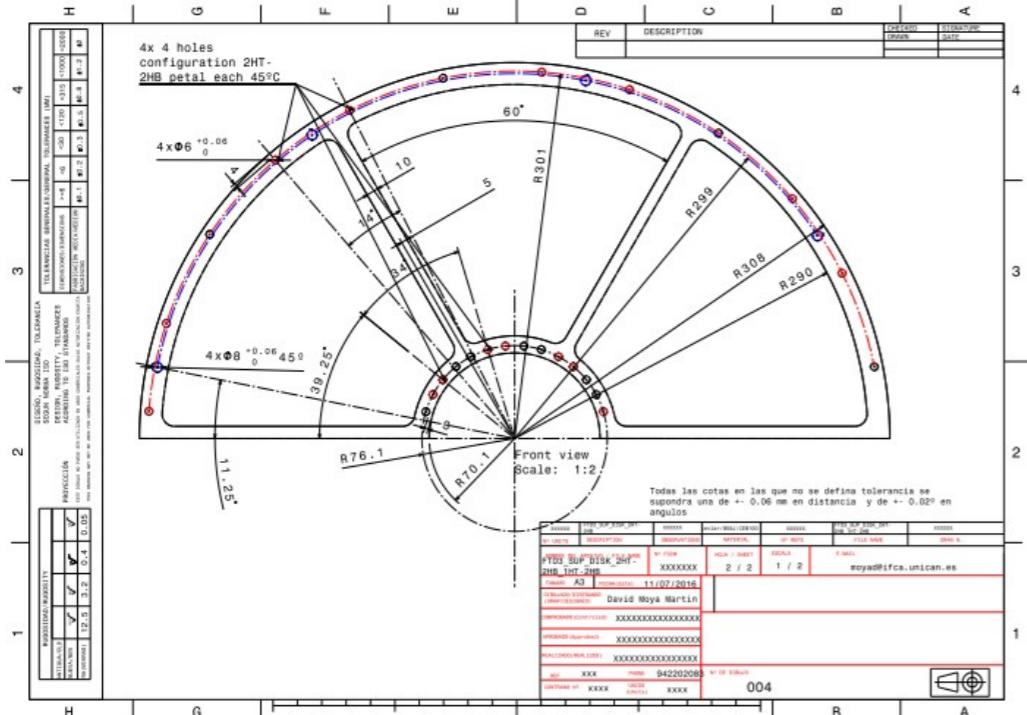
Thermo-mechanical properties



Assess initial mounting precision and stability
Monitor position stability under thermal load (20% of nominal DEPFET power)
Evaluate distortion under external forces (air flow, ...)



Mechanical characterization

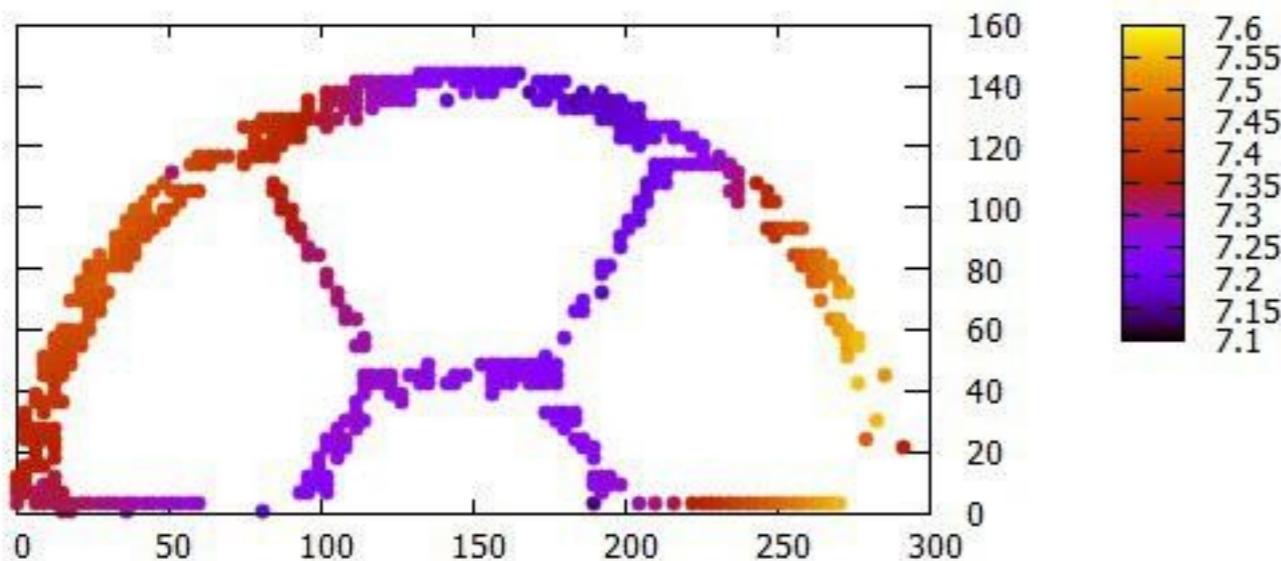


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Standard measurements of deformation under compression ASTM D695 M



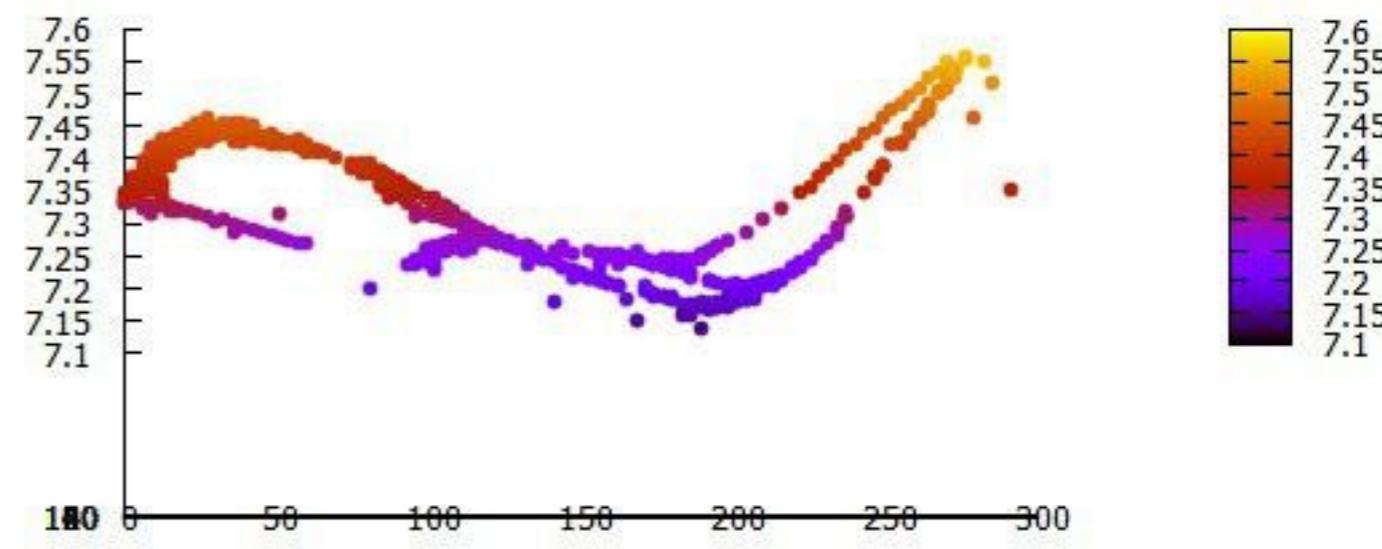
Planarity



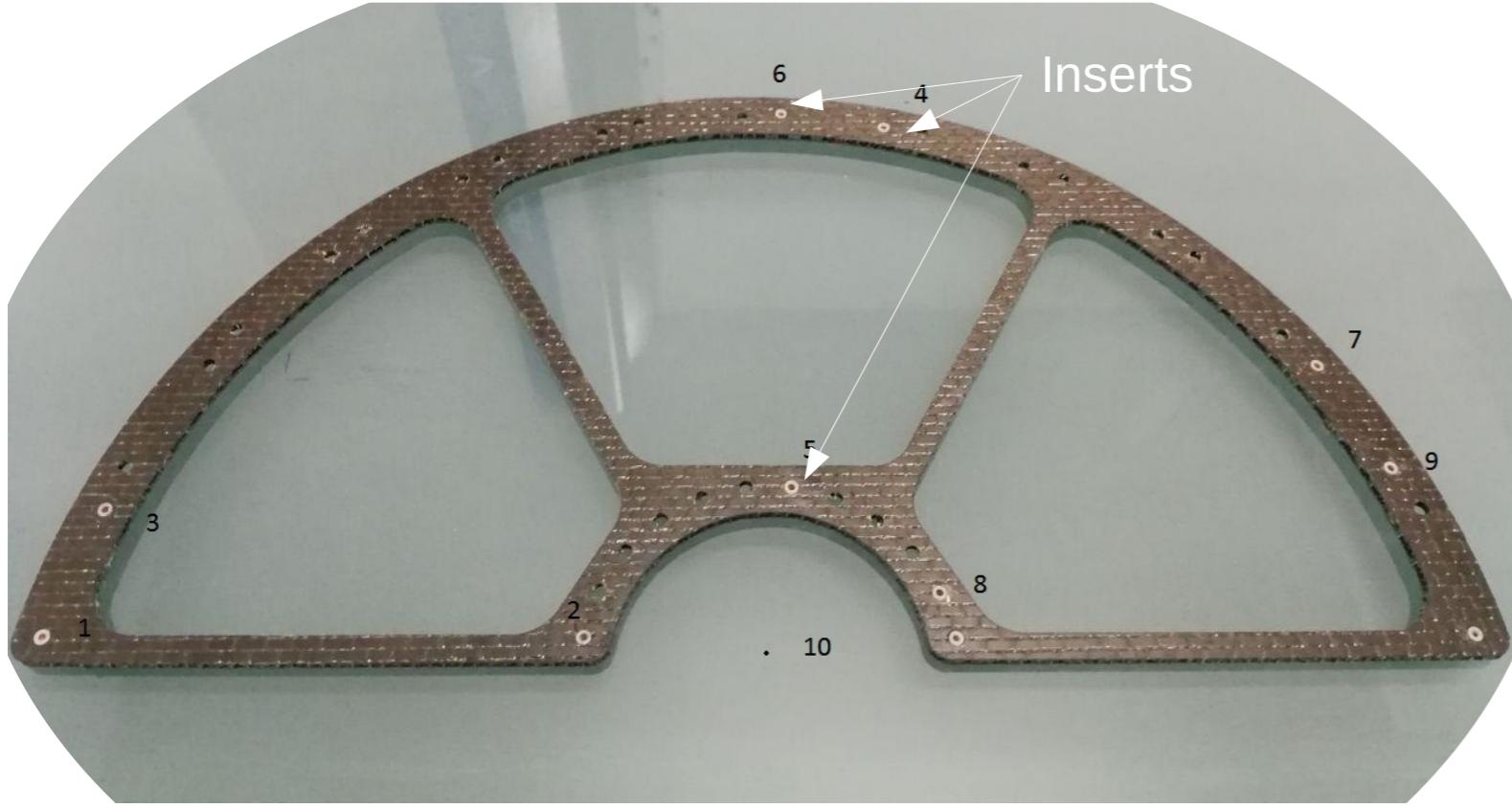
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Planarity over 30 cm:

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- RMS $\sim 200 \mu\text{m}$



Mounting & inserts

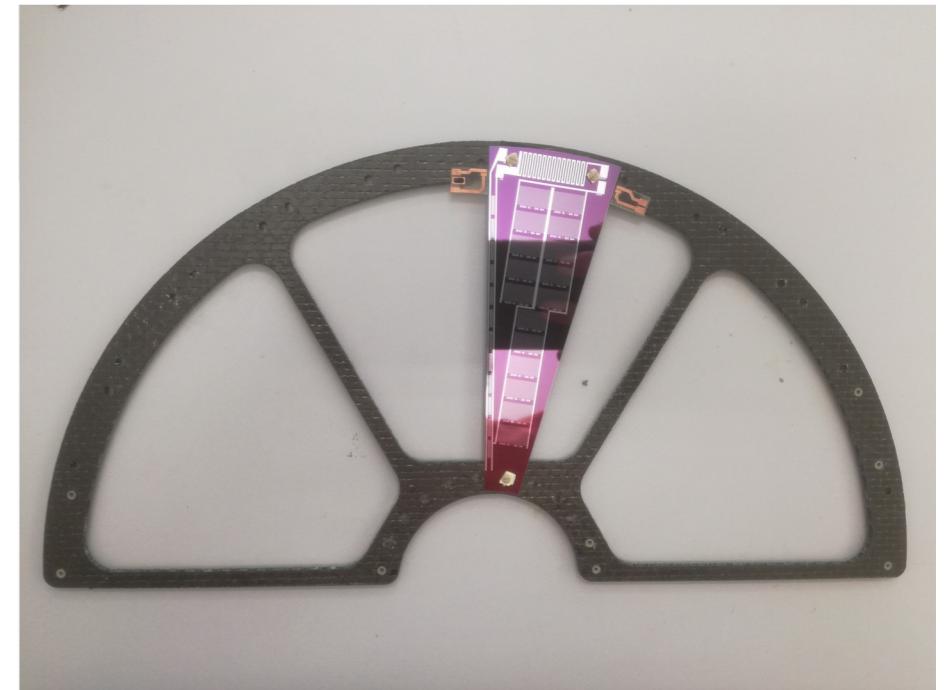


Planarity: 170 μm (RMS over 9 points, unloaded)

Placement precision of inserts: 100 μm (within triplet)

The mounting points for the silicon sensors are formed by PEEK precision inserts

Inserts are glued into the Carbon Fibre with a jig that guarantees good relative precision of the three mounting points for each sensor



Petals positioning

Holes produced in the carbon fiber with high precision machine, with $\pm 100 \mu\text{m}$ tolerance

PEEK inserts placed in holes with a precision jig, to achieve better placement precision of the Silicon sensors

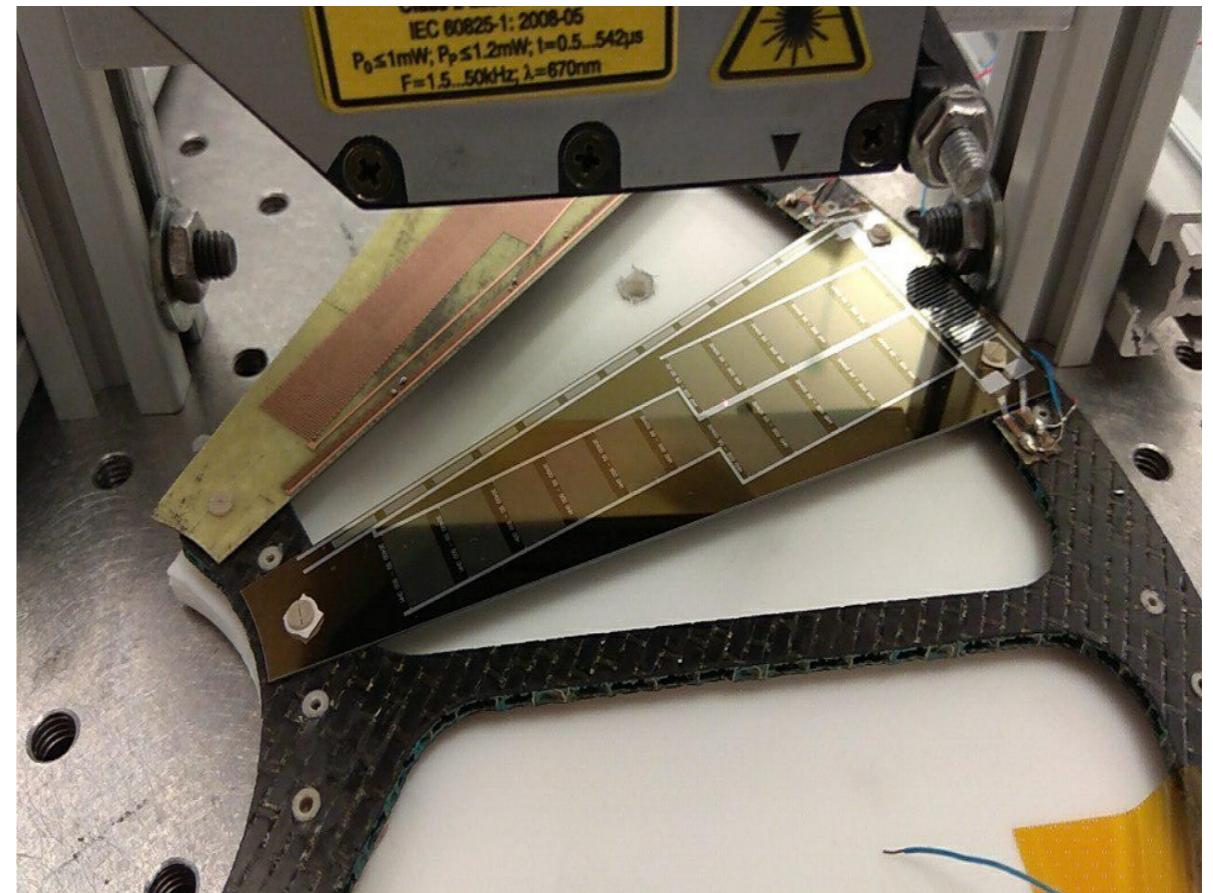


Mounting the Silicon petals

Controlled torque



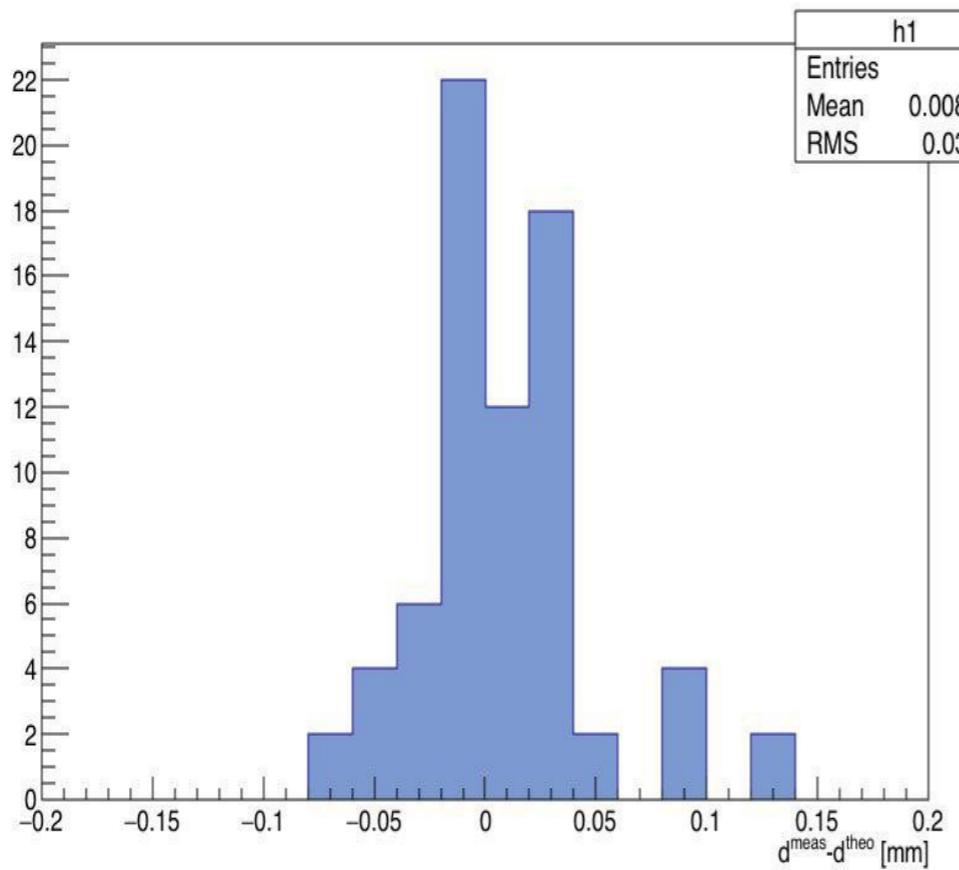
Position, deformations and vibrations measured precisely



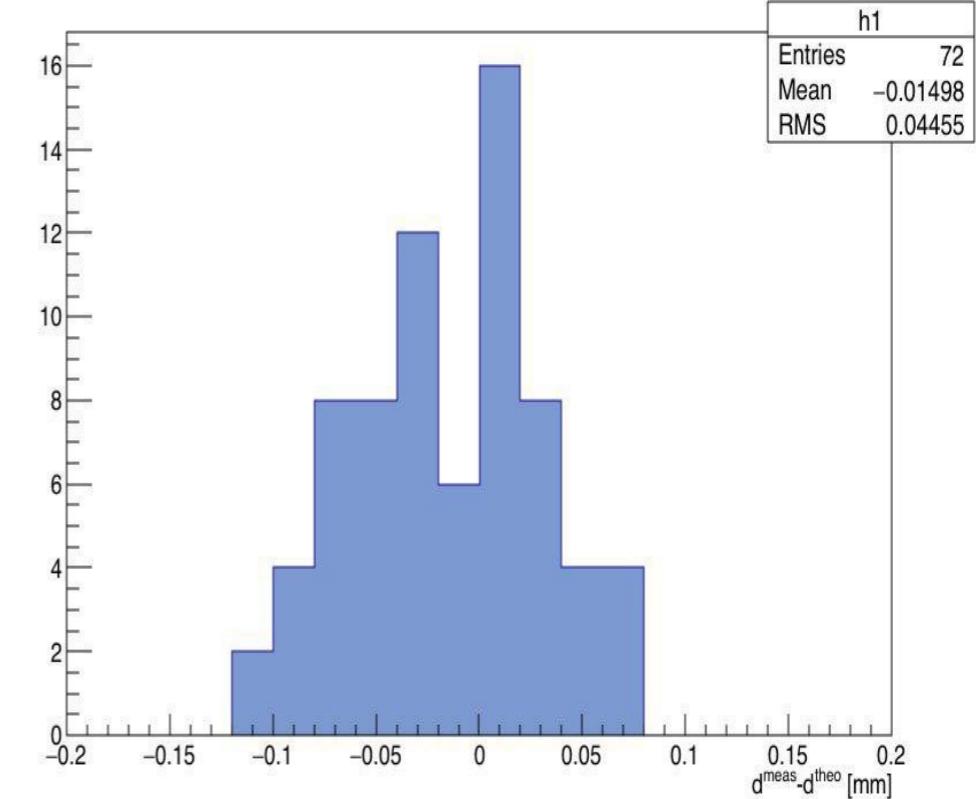
Petals positioning

Relative precision of the PEEK inserts:
 $\pm 50\text{um}$ from nominal position

FTD1



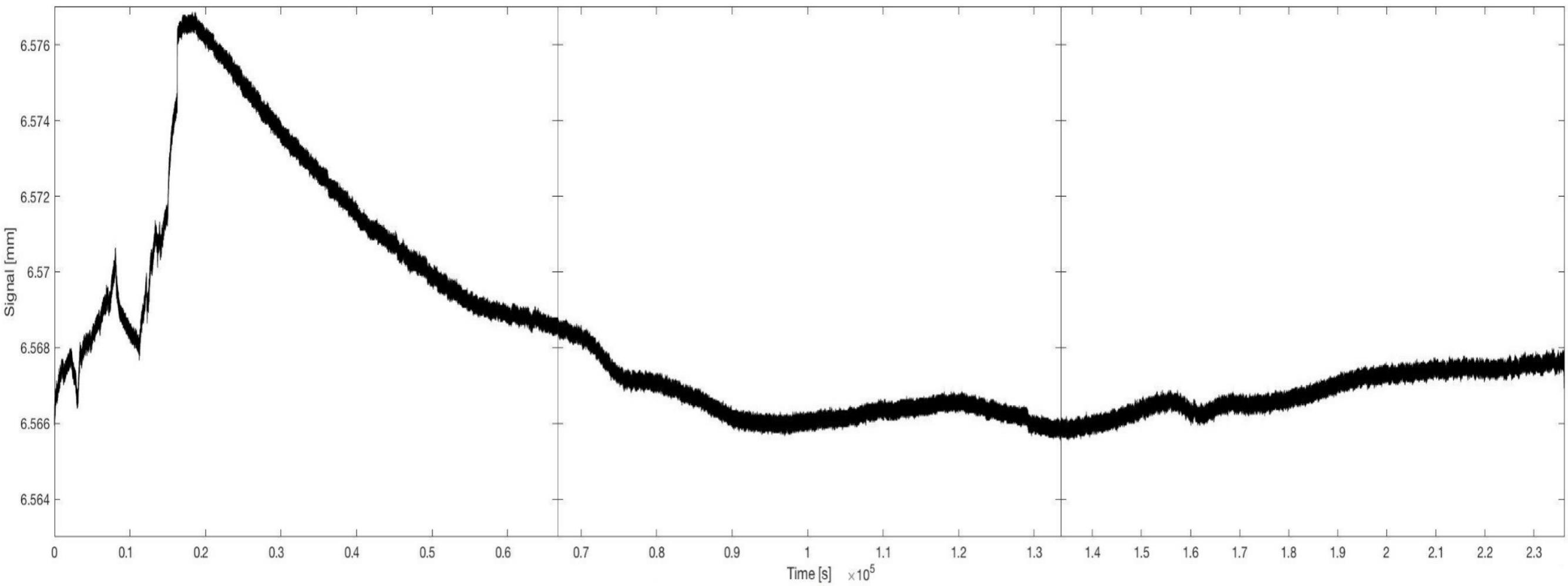
FTD2



Petals stabilization

Deformations due to background vibrations and temperature variations is stable within 48 hours between $\pm 1\text{um}$ in Z

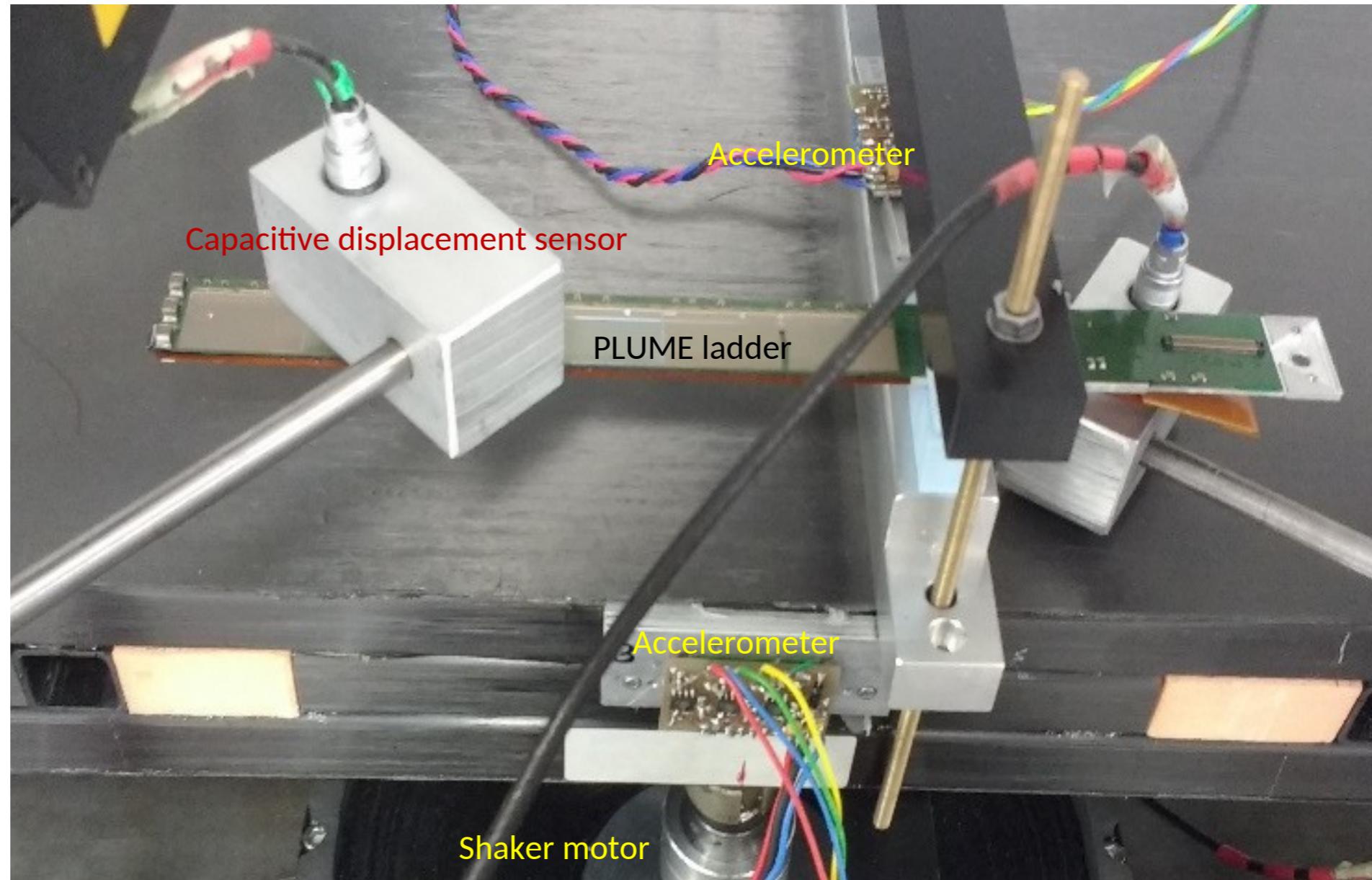
A 1 day transitional period of time needed before stabilization



Vibration setups developed at Oxford with AIDA2020 support

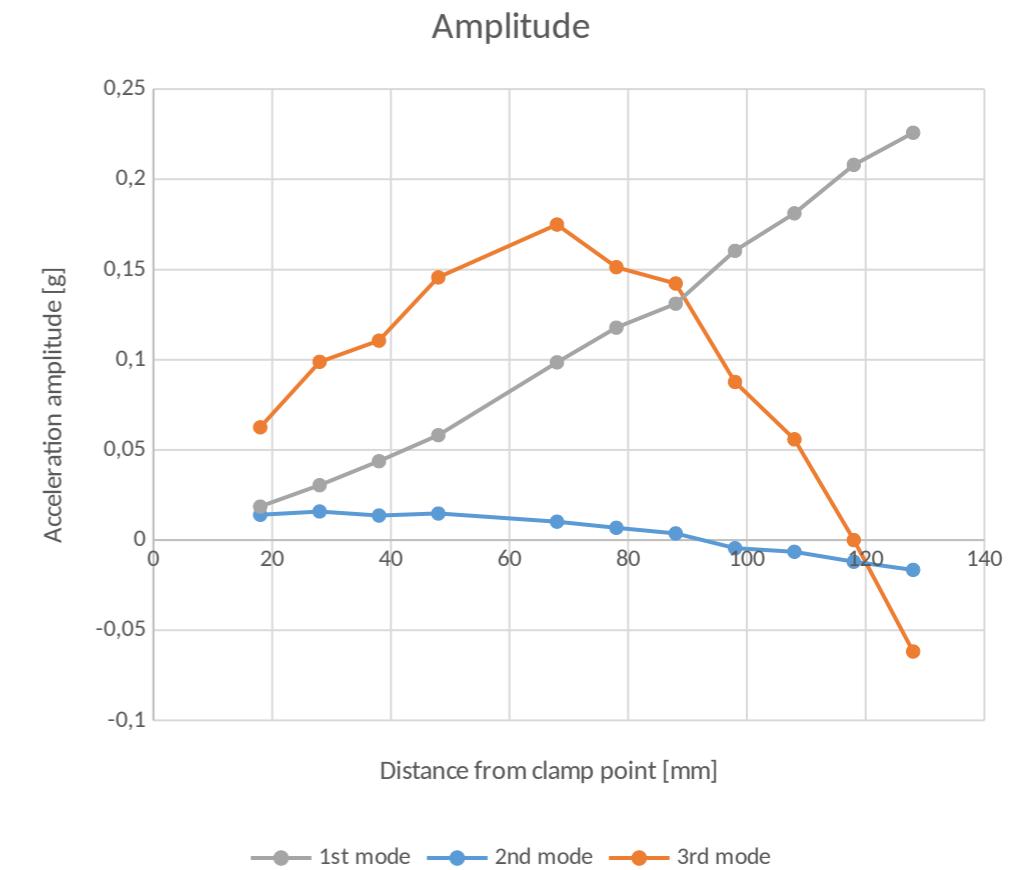
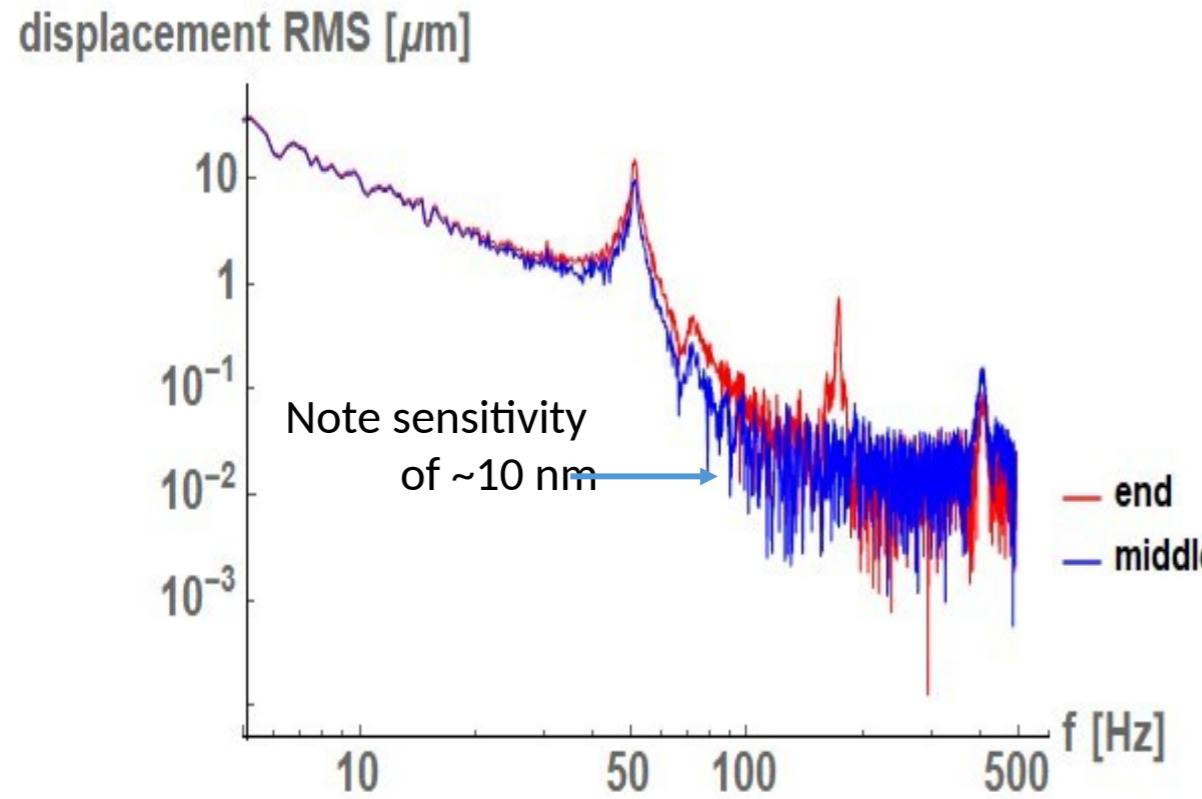
Shaker table:
controlled
mechanical
“noise” injection

First client:
PLUME ladders
J. Goldstein,
Bristol



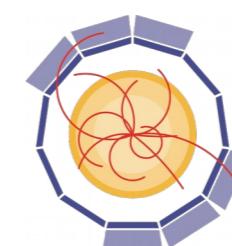
From G. Viehhauser

Mechanical performance: vibrations



- Identify resonance frequencies
- Repeat measurements along the ladder → modal analysis

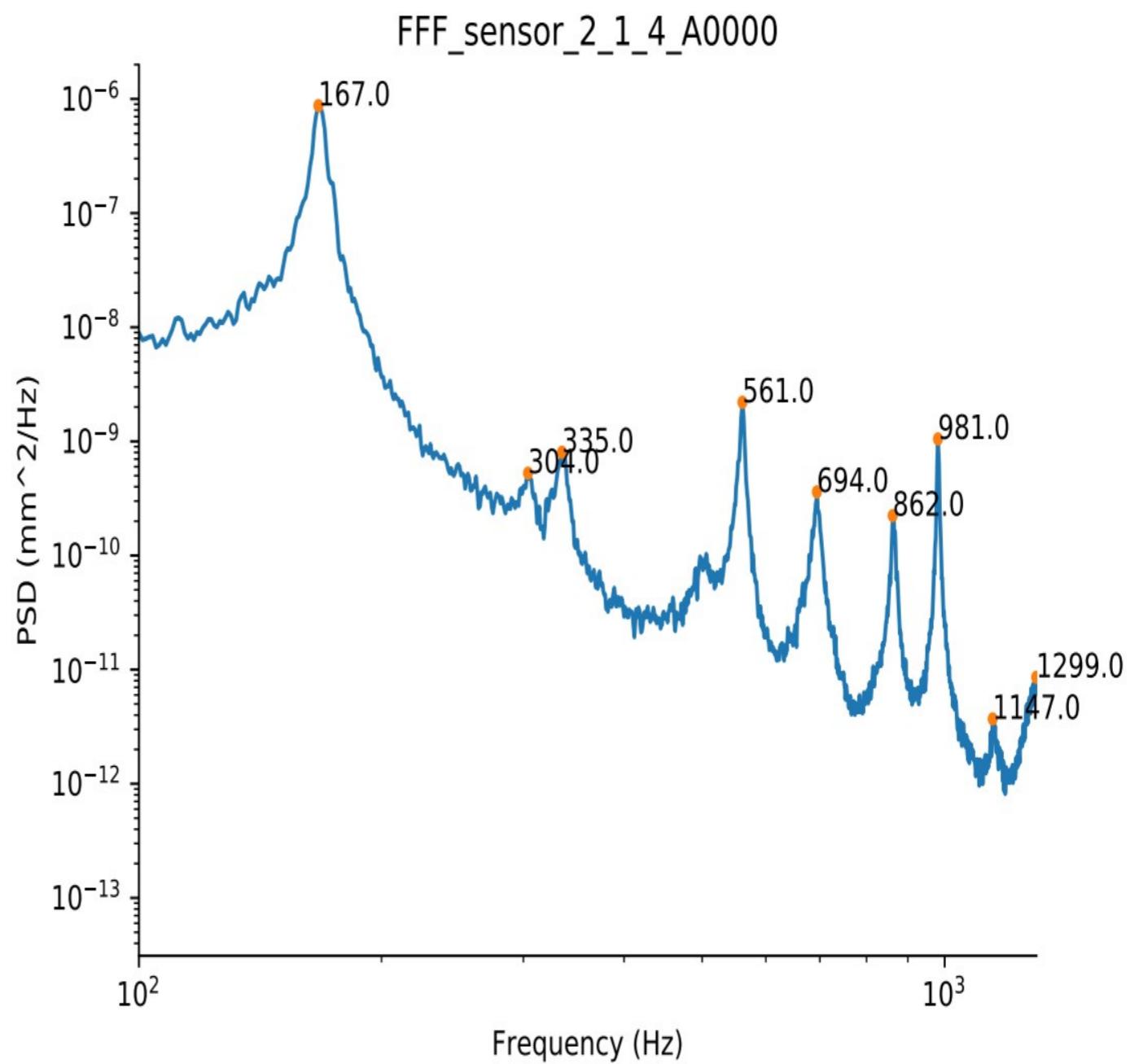
From G. Viehhauser





Petals modal analysis

Reference measurements
Free: no torque applied to screws

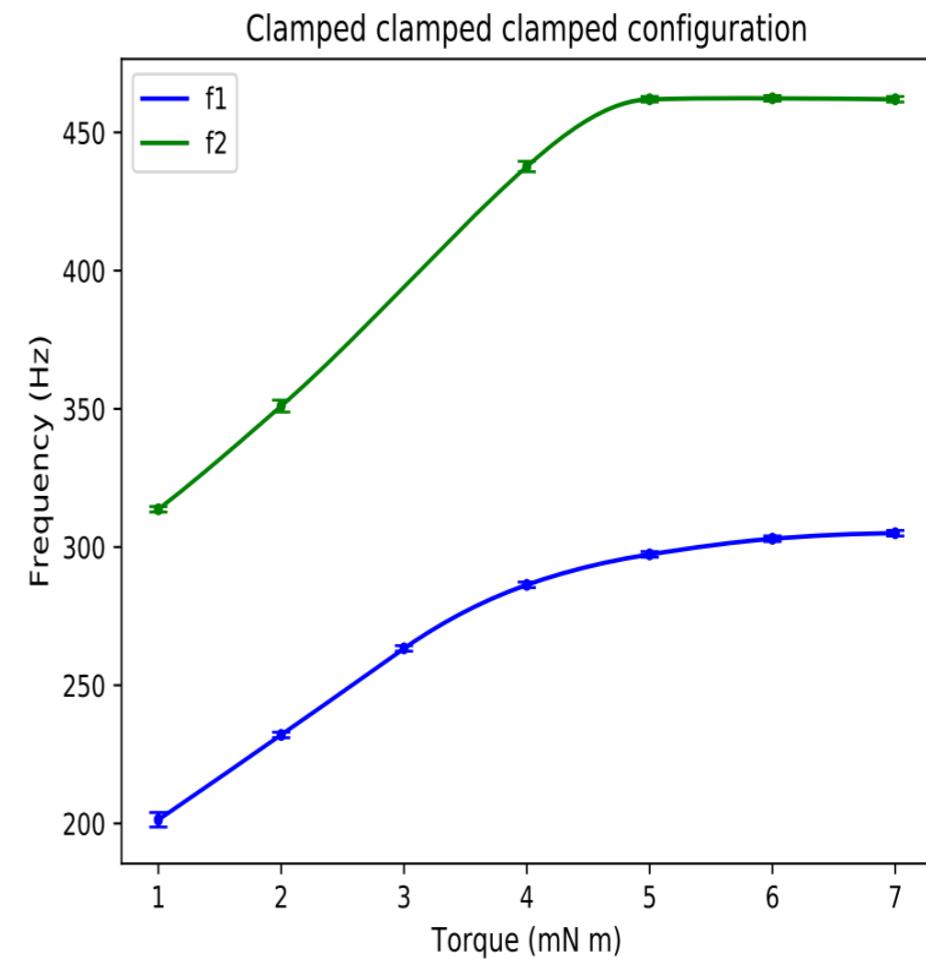


Petals modal analysis

The natural vibration modes (eigenfrequencies) are measured as a function of the torque applied on the screws that fix the Silicon on the three mounting positions

The eigenfrequency increases with the torque applied to the screws
(the joints are elastic; petal degrees of freedom are modified as the torque increases)

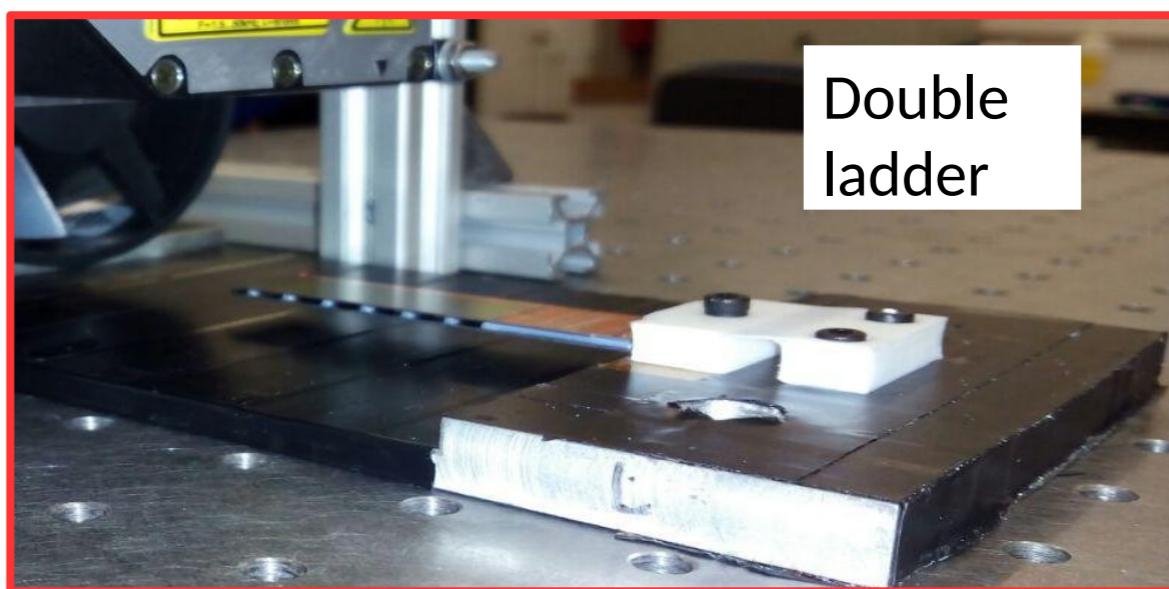
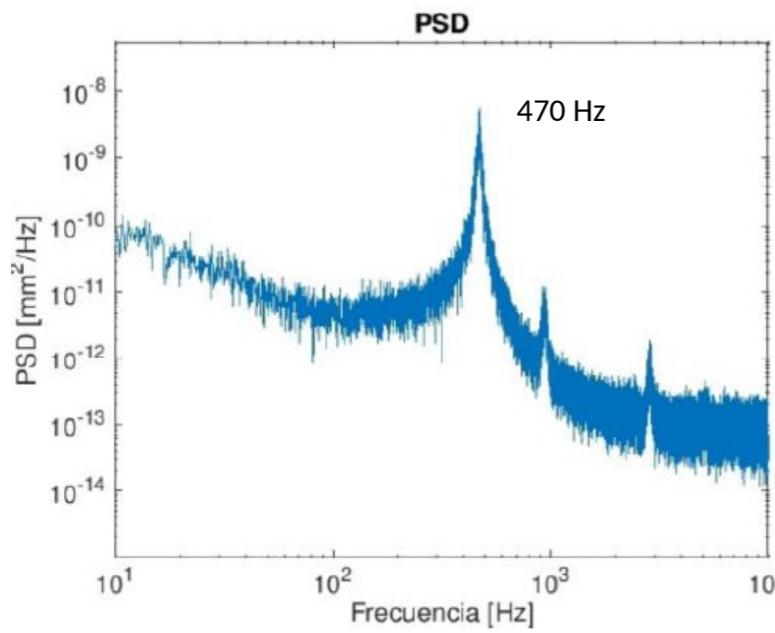
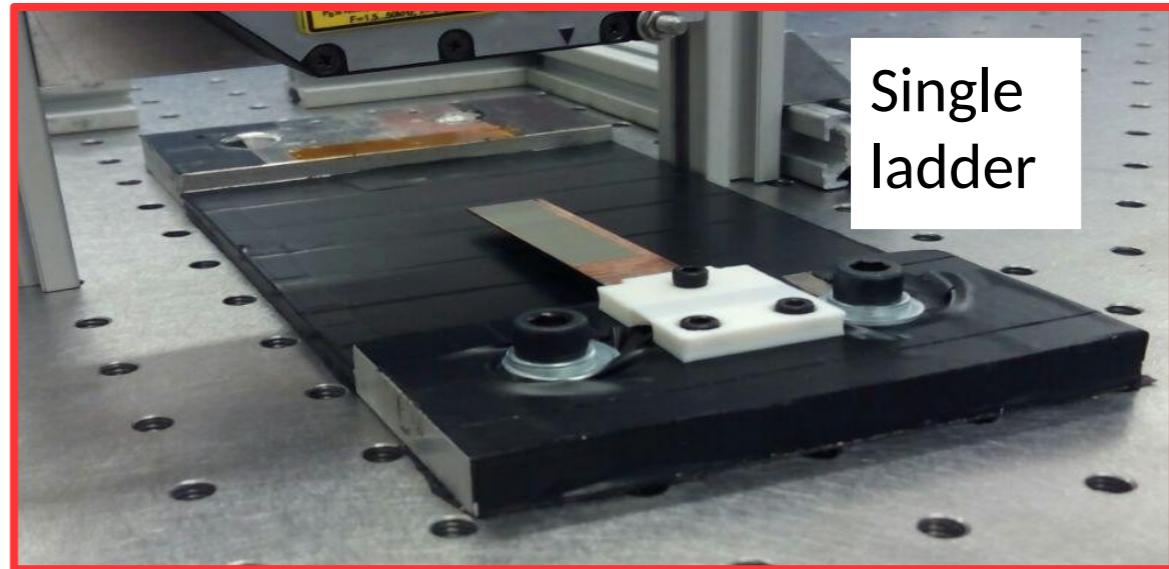
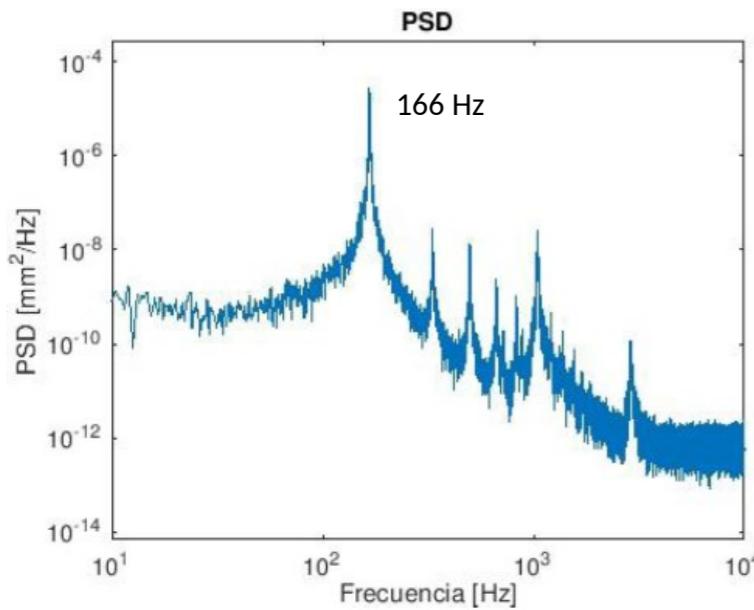
The eigenfrequency saturates at about 300 Hz



0,3 – 0,5 cN·m for a completely clamped petal

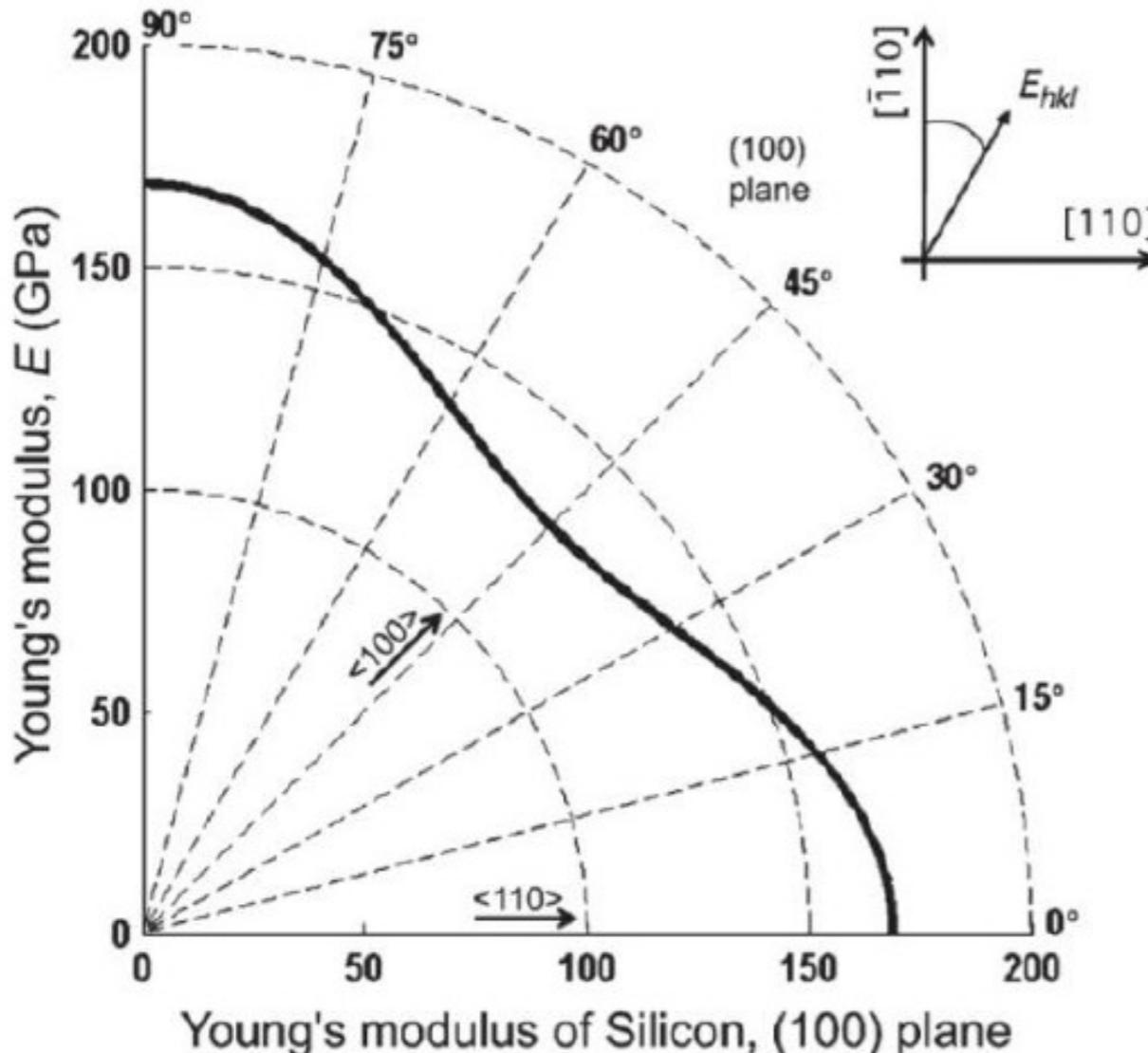


Mechanical performance: vibrations



Eigenfrequencies are easy to measure (and closely related to stiffness)

Young's modulus



Bachelor's thesis of Yamal Nasser Requena at U. Valencia, supervised by Guillem Vidal (IFIC)

Mechanical properties, i.e. Young's modulus, can be extracted with good precision:

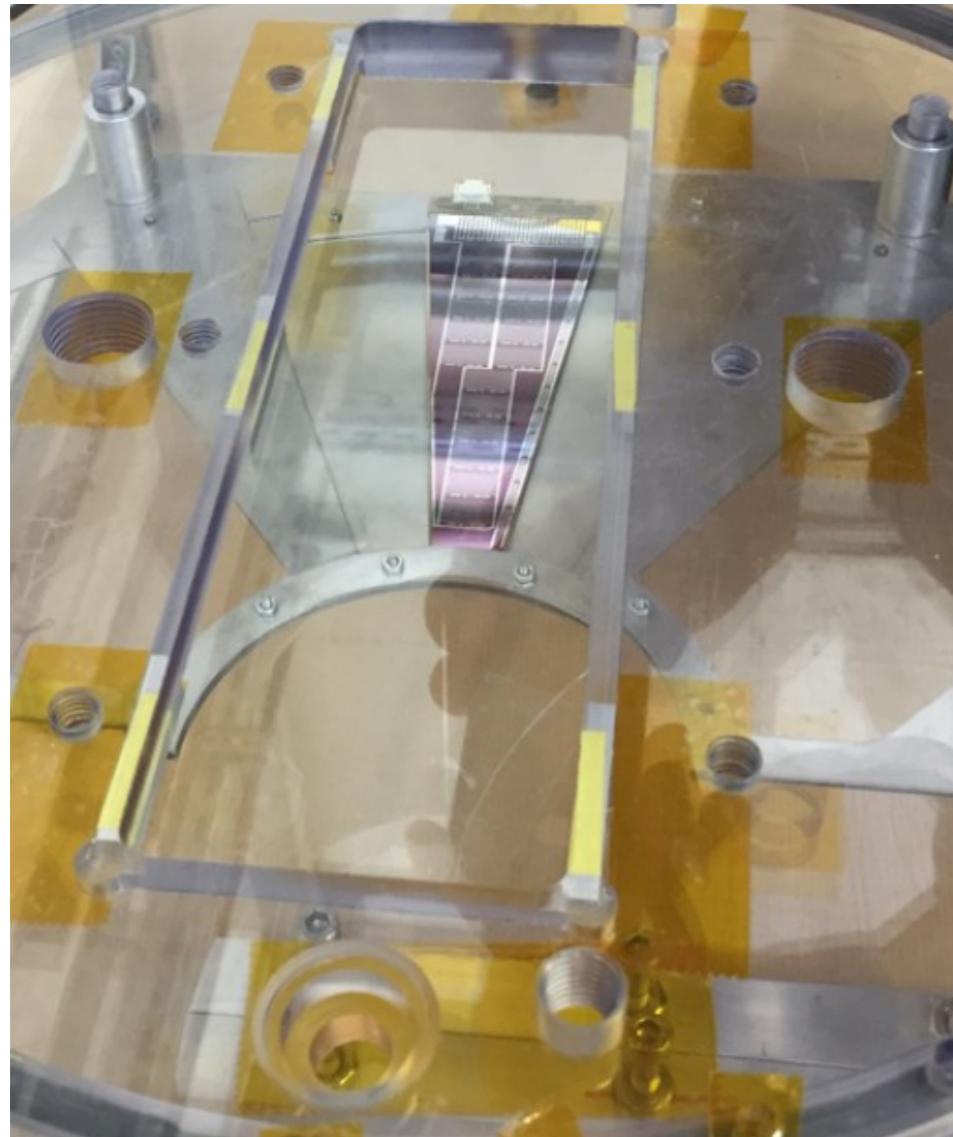
140 ± 10 Gpa

Inspired in part by Georg Viehhauser's paper:
JINST 10 (2015) no. 9, P09001

To be developed further:

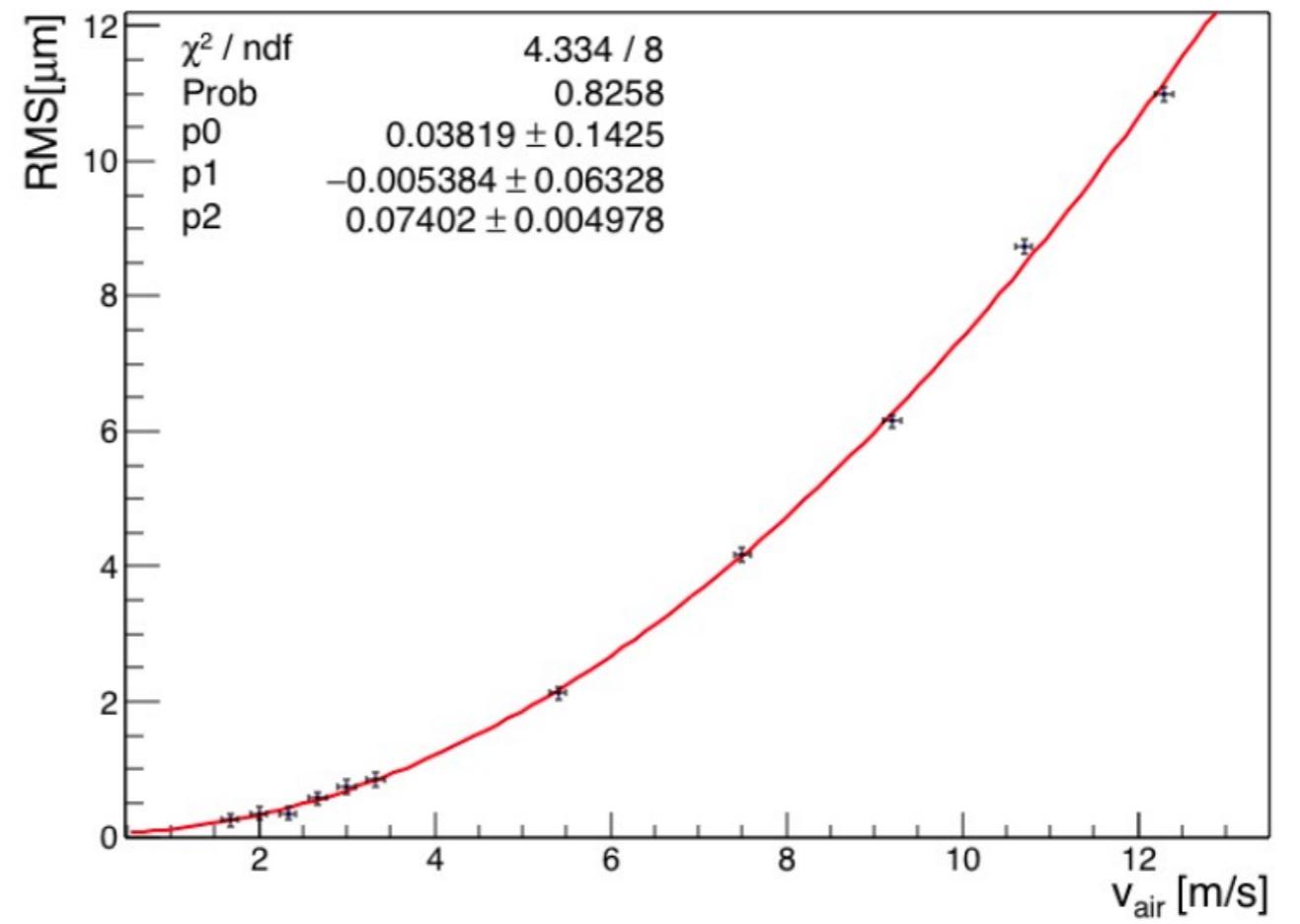
- determination of “load” spectrum due to vibrations in experiment, air cooling, etc.
- vibration measurements for QA/QC of complex structures

Air cooling & mechanical stability



Petal in CLIC d&p wind tunnel (F. Duarte)

Vibrations remain acceptable for air speed up to several m/s

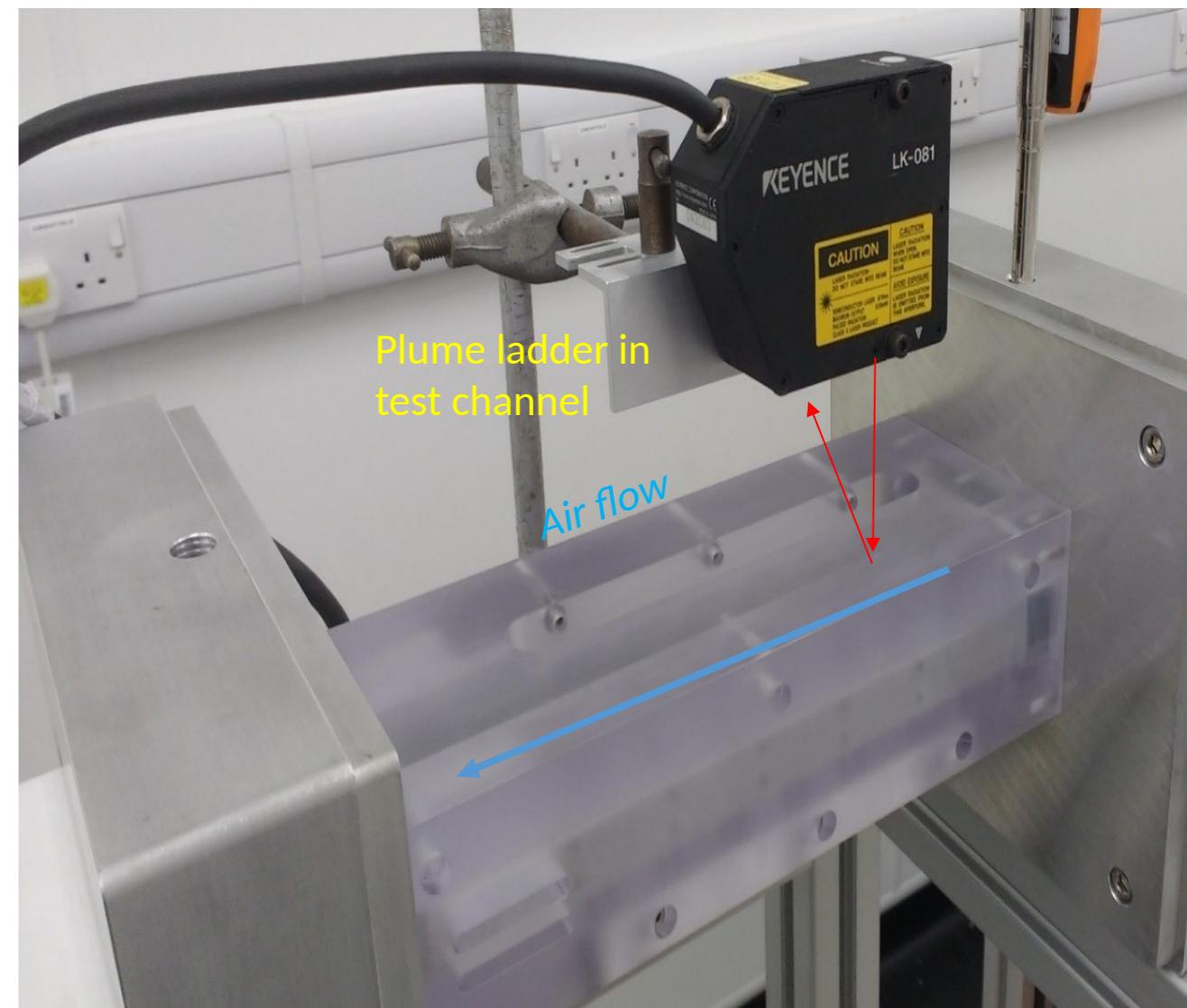


Ph.D. thesis Nacho Garcia,
U. Valencia, 2016



Air flow setup

- Air cooling is needed to meet requirements of e^+e^- detectors
- Already used in STAR-HFT, and Belle II pixel detector, ...
- Potential, limitations and threats still poorly understood
- The main AIDA2020 development in Oxford
- Wind tunnel setup can monitor deformations and vibrations vs. controlled air flow

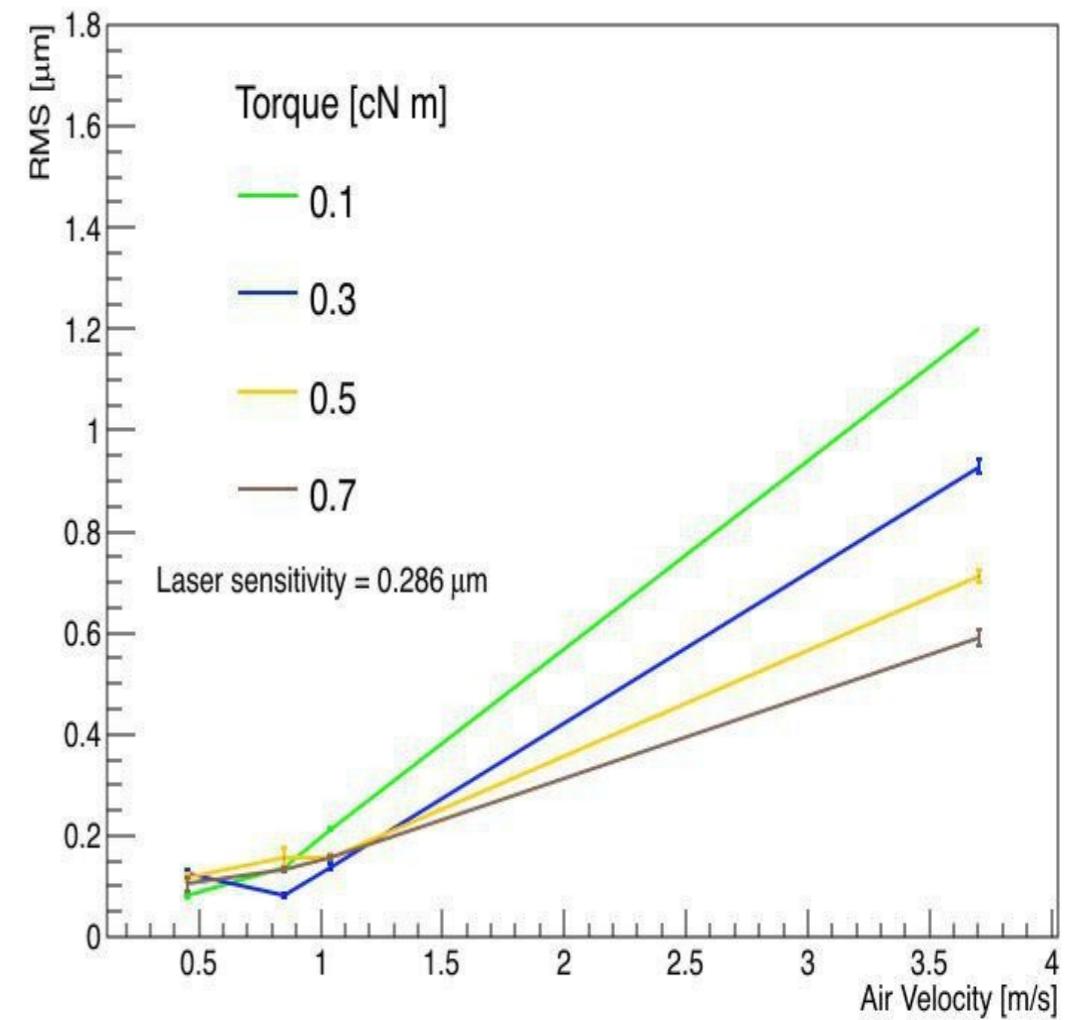
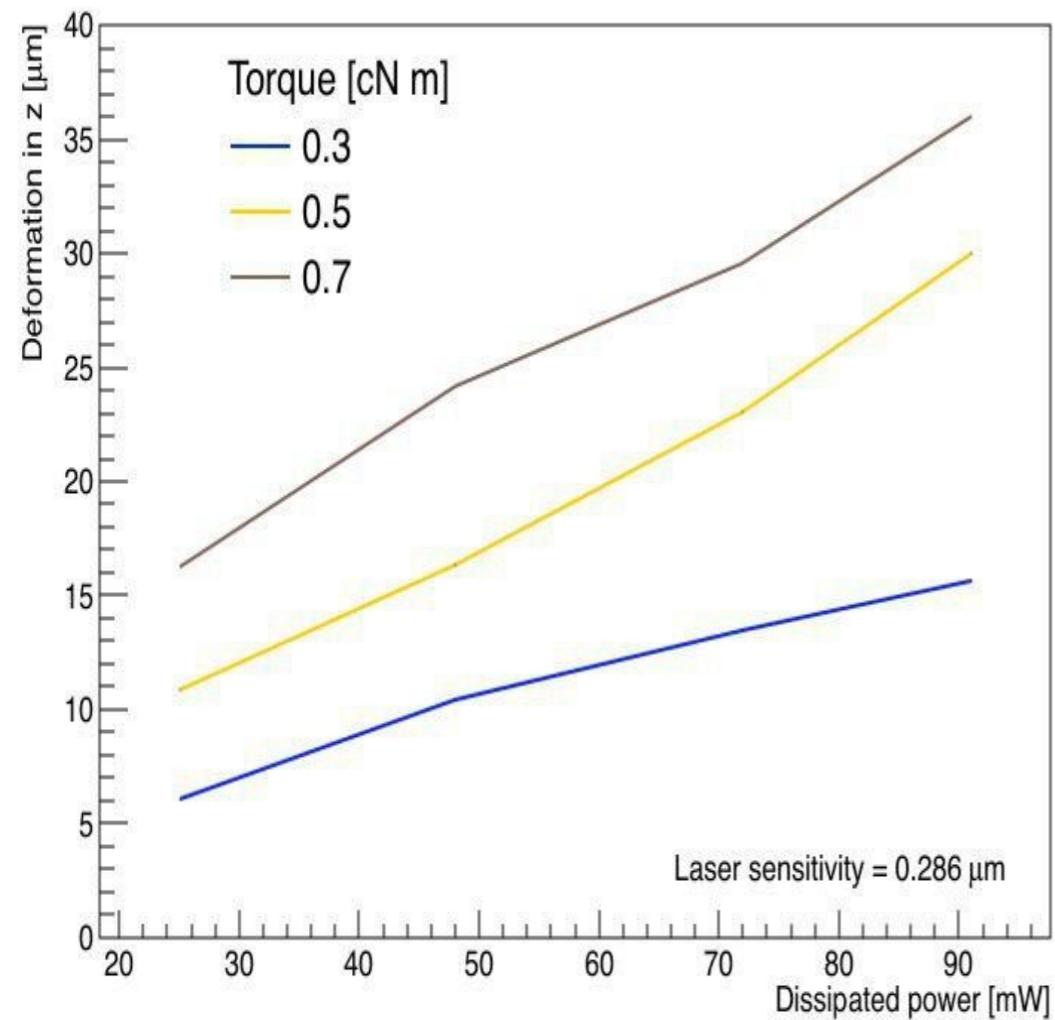


Petal deformations vs. air velocity

Measurements repeated on CF disk, with the petal clamped in a fully controlled way

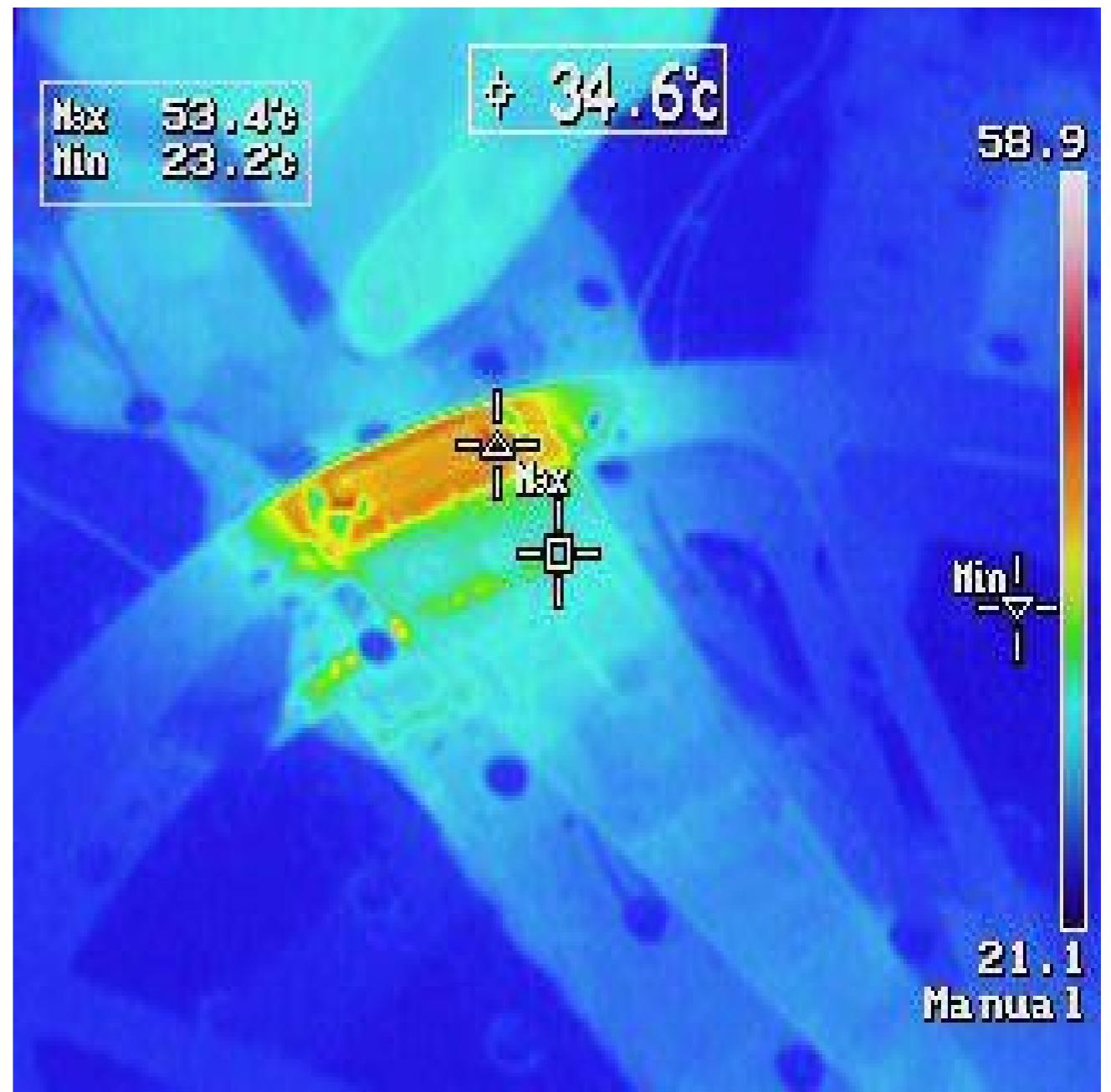
Deformations due to thermal expansion of the sensor are sizeable: 10 μm when not cooled

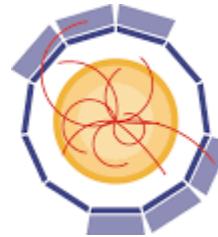
Deformations due to laminar air flow increase with air velocity: less than 1 μm up to 4 m/s



Measurement in realistic conditions

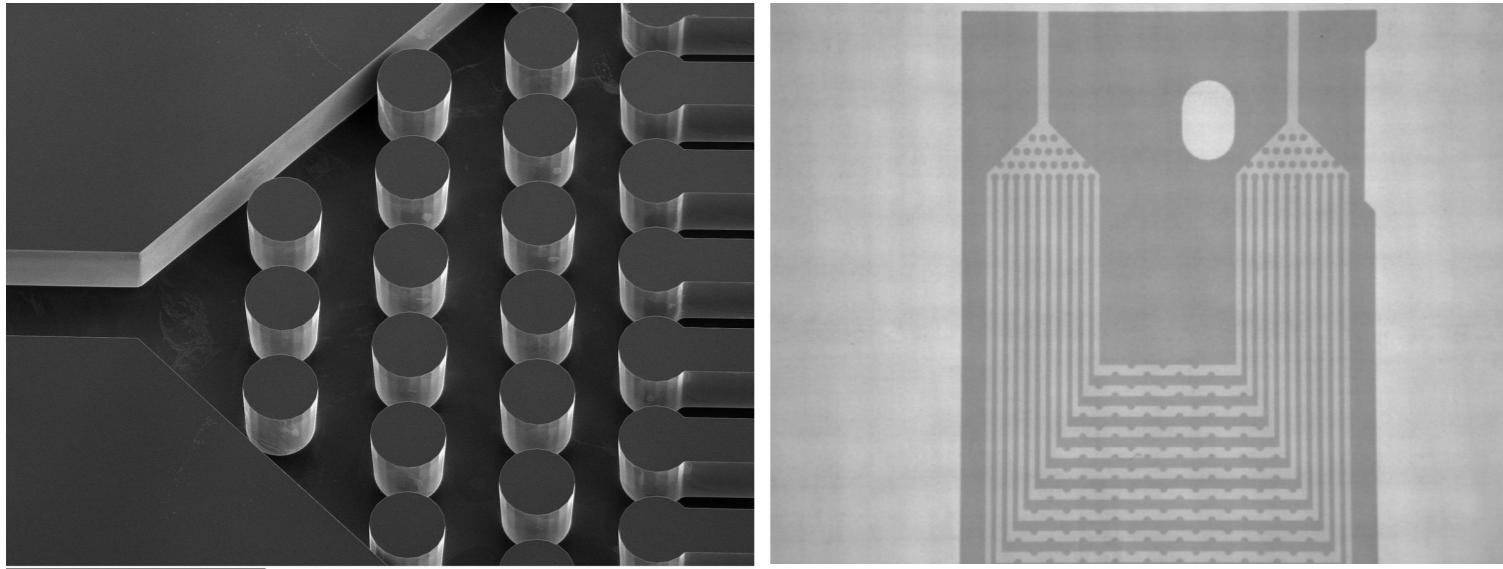
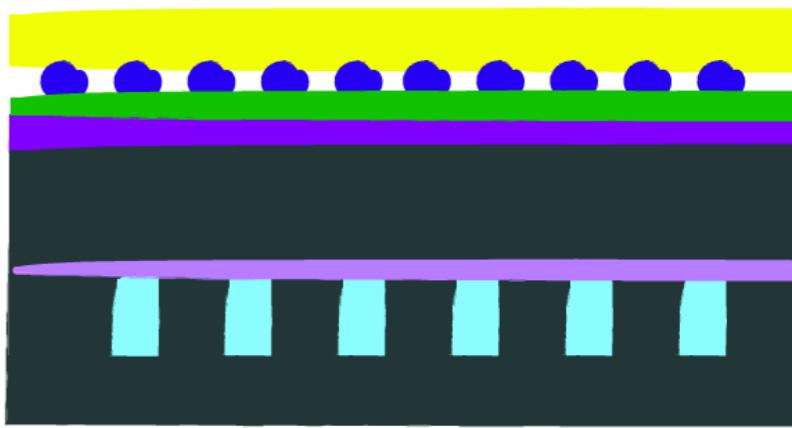
For a maximum temperature gradient over the sensor area of 10K, air cooling at 1m/s is sufficient for nominal power
→ RMS of 0,2 - 0,4 μm .





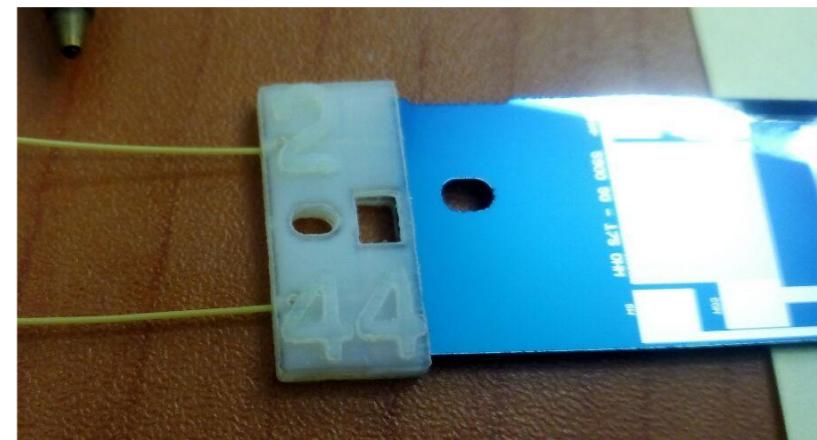
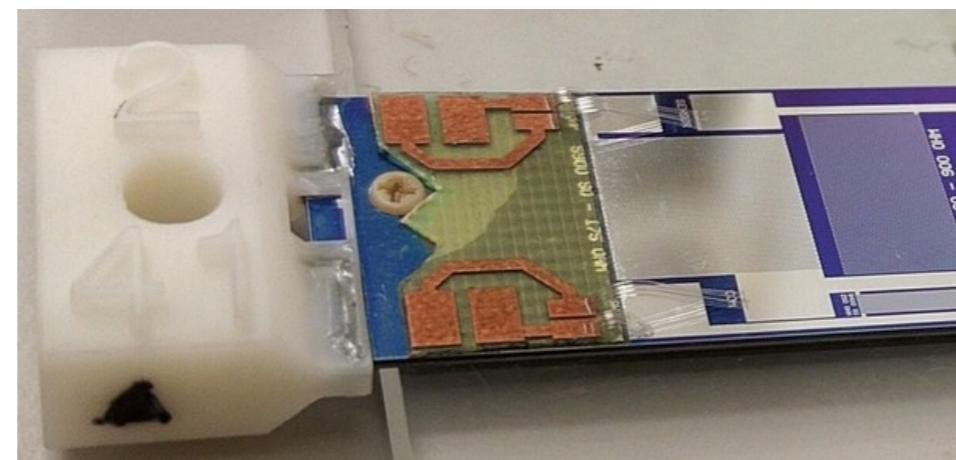
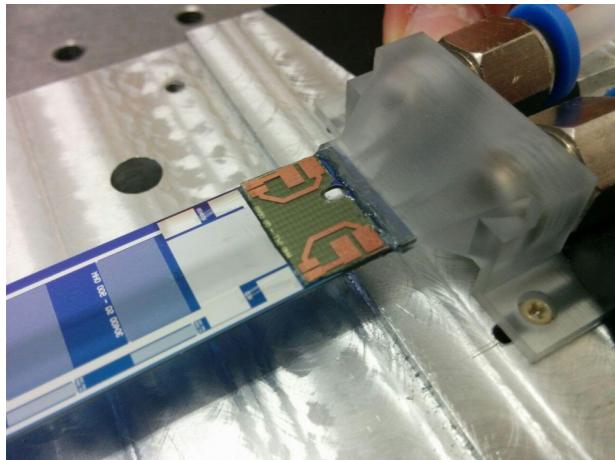
AIDA²⁰²⁰

Cooling + supports



*Micro-manifold before (photograph) and After wafer bonding (X-ray image)
Samples produced at HLL.*

(arXiv:1604.0877)



High-tech plumbing: custom, 3D-printed interfaces to commercial piping

Integrated μ -channels at IFIC, with U. Bonn & MPG-HLL
→ see Paolo's talk in this session



Summary

Produced a complete mechanical prototype for forward tracking disks based on all-silicon petals (MPG-HLL) and ultra-thin CF support structure (INTA)

Evaluation of thermo-mechanical performance in realistic conditions is ongoing

First measurements look promising:

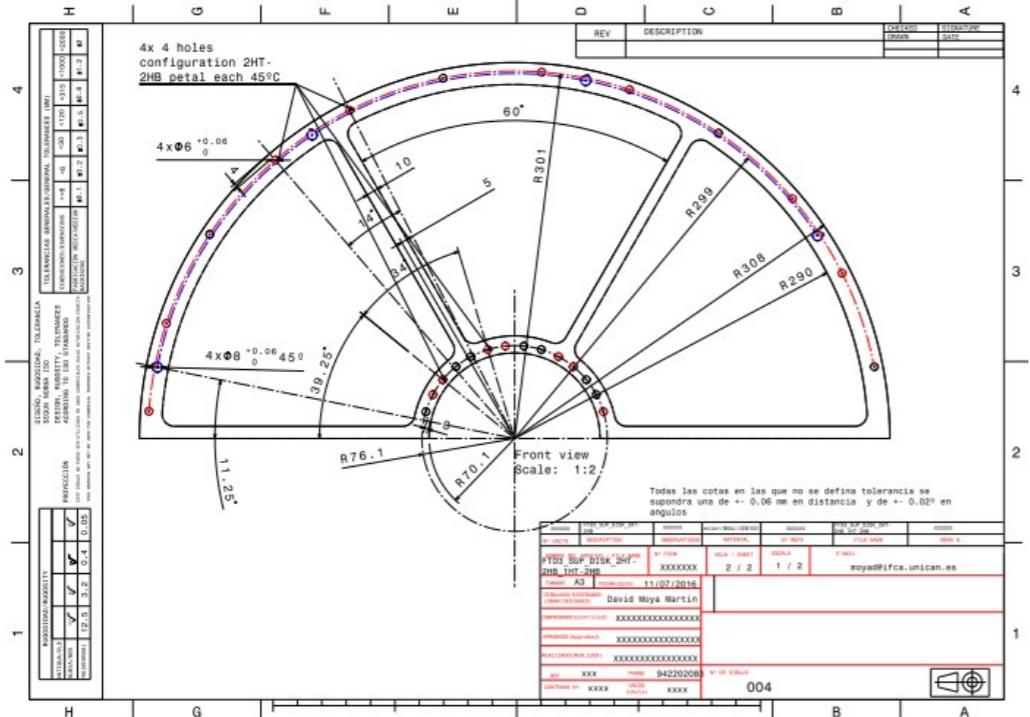
- material budget meets requirements
- kinematic mount absorbs thermal expansion as expected
- gentle air flow sufficient to cool nominal power (including 20% duty cycle)
- slow deformations when establishing power load and air-flow are $O(5 \mu\text{m})$
- vibrations due to air flow and from external sources controlled sub- μm

A step towards a realistic design of a forward tracker for a LC experiment

Perspective: gaining confidence that the silicon detectors of an e^+e^- collider experiment can be built, using air cooling (where possible) and integrated -channel cooling (where we need control)



Mechanical characterization

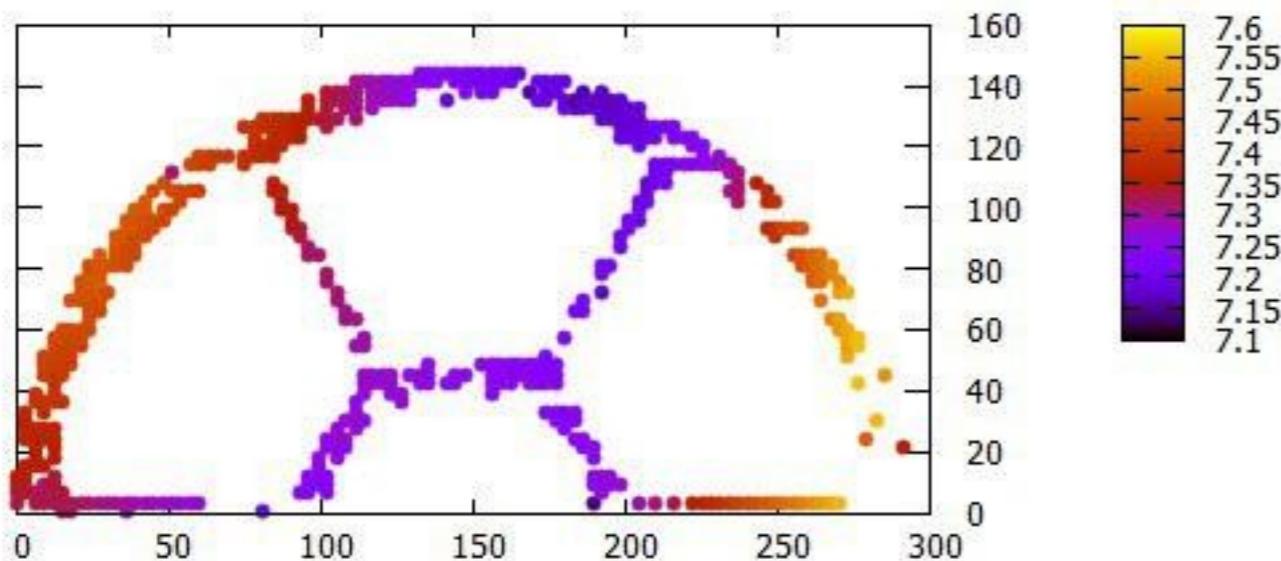


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Standard measurements of deformation under compression ASTM D695 M



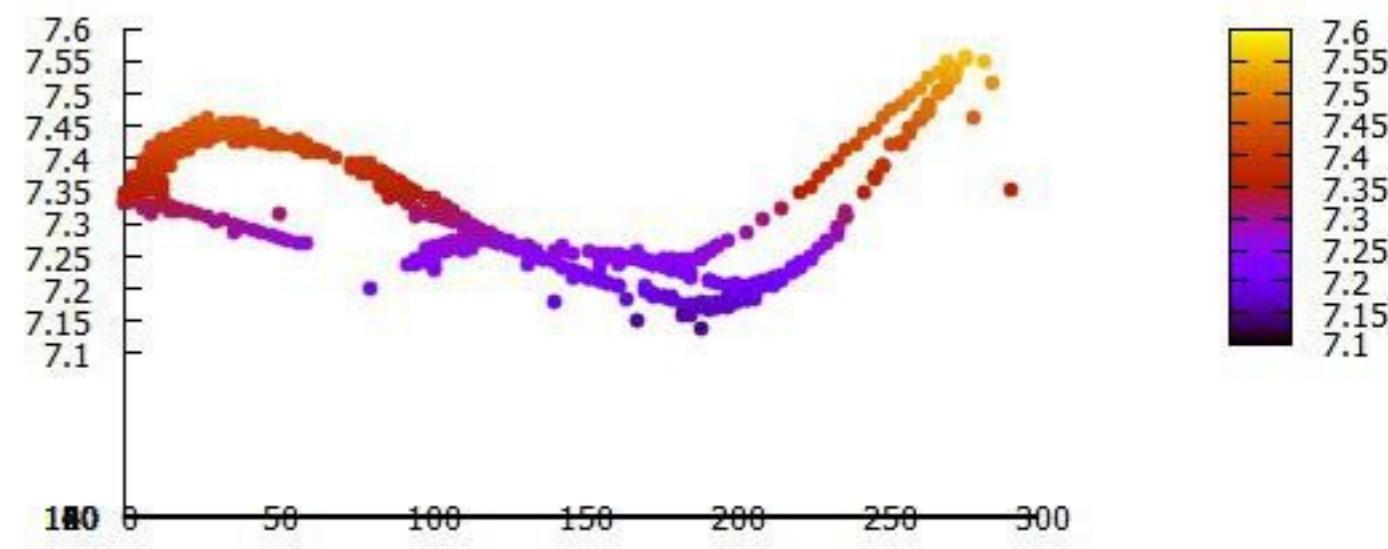
Planarity



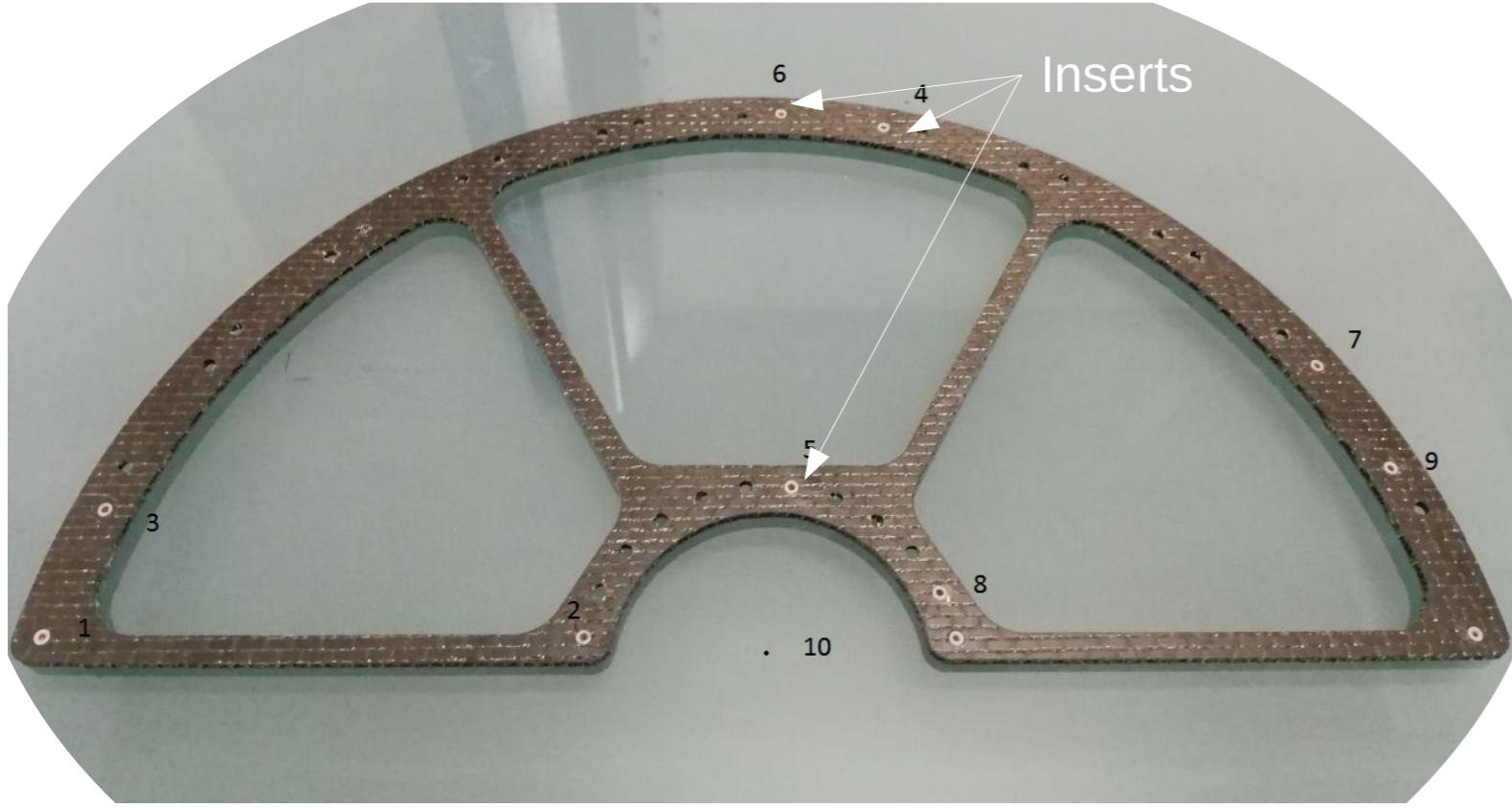
The CF disks have been extensively surveyed in a precise metrology system.

Planarity over 30 cm:

- peak-to-peak $\sim 500 \mu\text{m}$
- RMS $\sim 200 \mu\text{m}$



Mounting & inserts

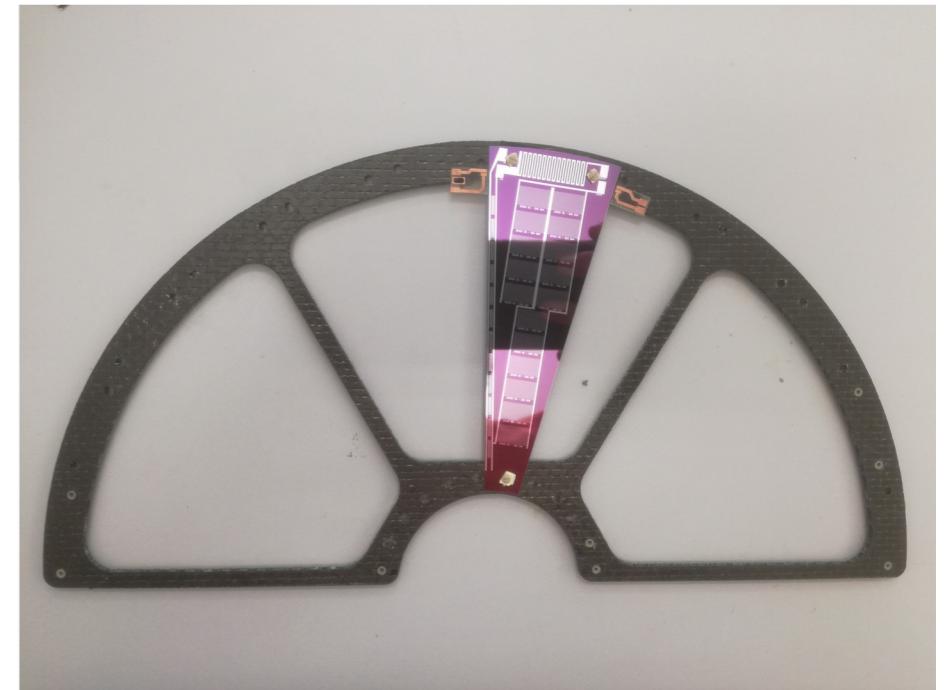


Planarity: 170 μm (RMS over 9 points, unloaded)

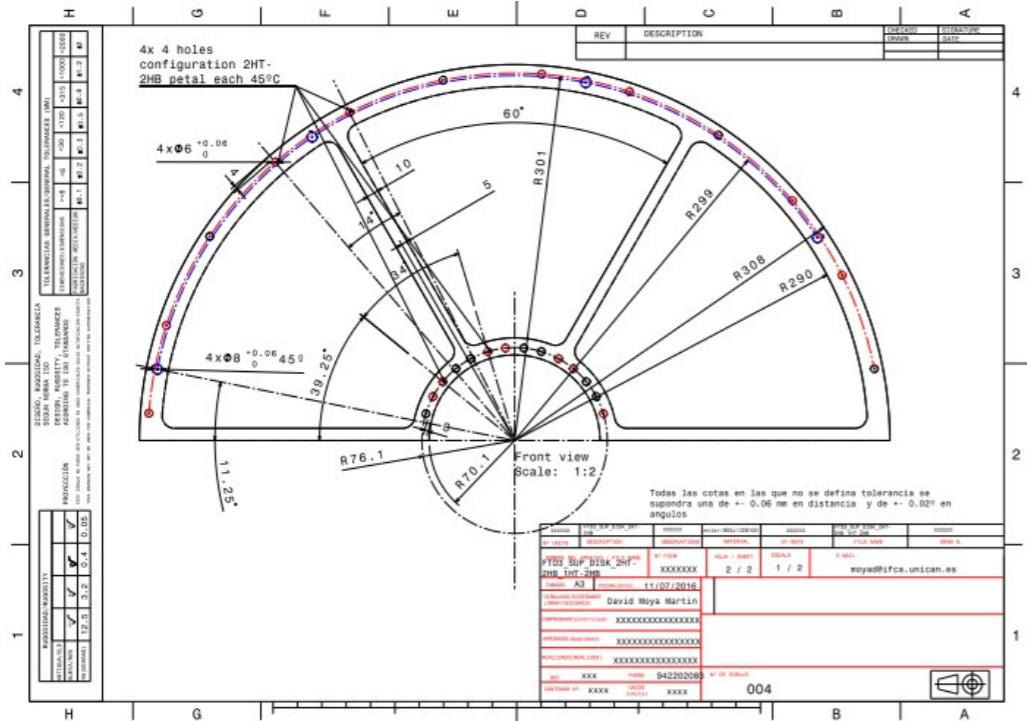
Placement precision of inserts: 100 μm (within triplet)

The mounting points for the silicon sensors are formed by PEEK precision inserts

Inserts are glued into the Carbon Fibre with a jig that guarantees good relative precision of the three mounting points for each sensor



Mechanical characterization

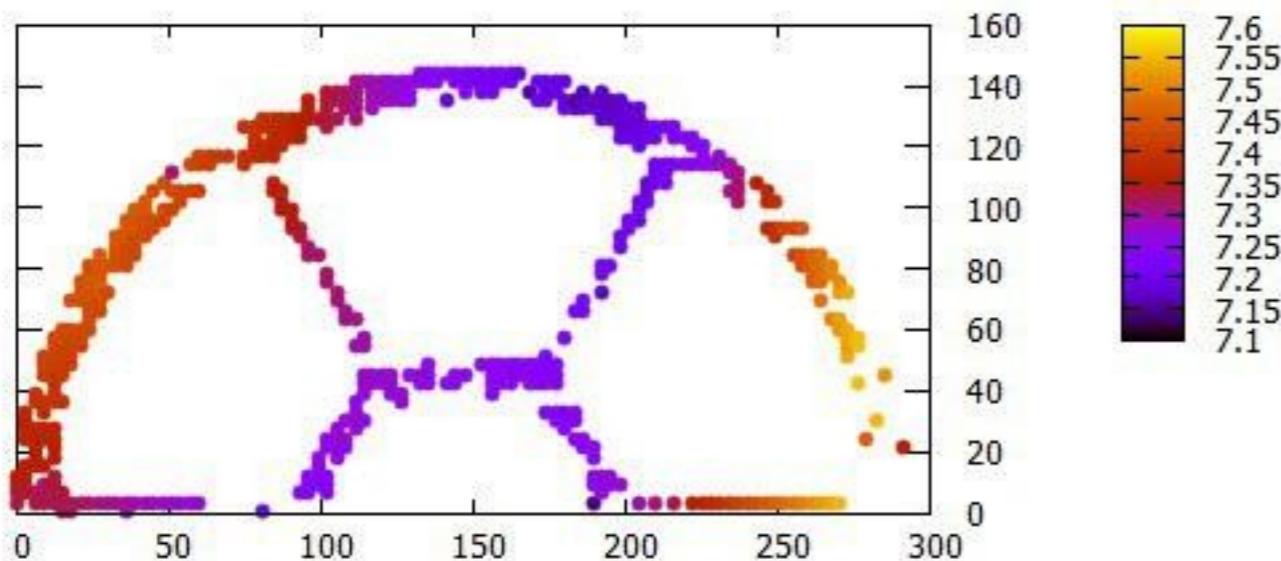


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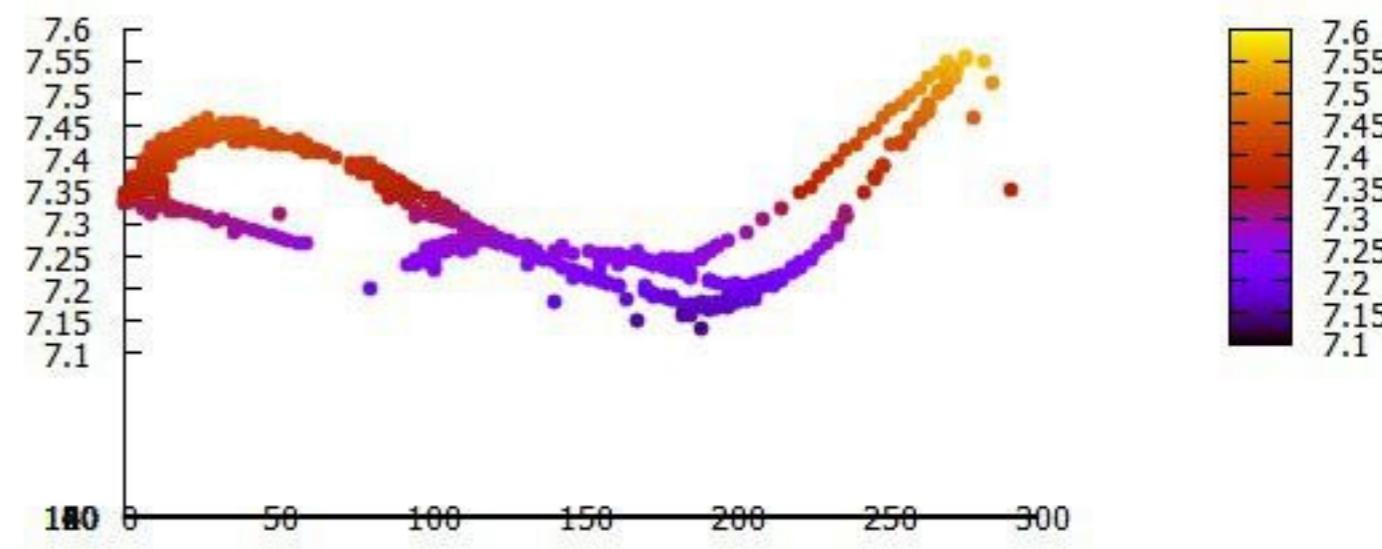
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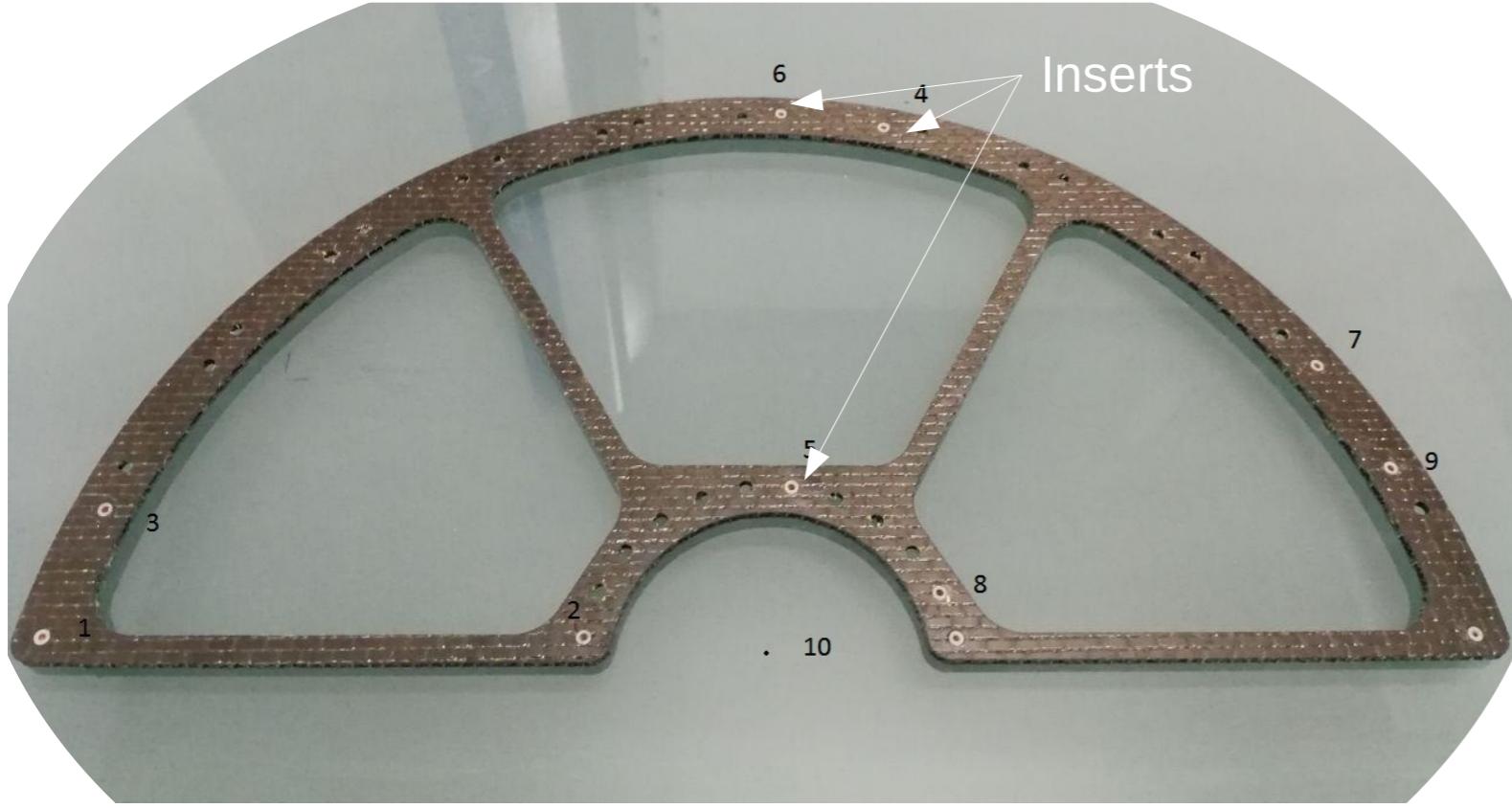
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