# Silicon Detector Activities for Belle II and CMS Experiments

**K. Kameswara Rao**
(on behalf of the TIFR Belle II and CMS-HGCAL teams)
Dept. of High Energy Physics
TIFR, Mumbai

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# Outline

- Layer 4 for Belle II Silicon Vertex Detector (SVD)
  - Design, prototyping and construction
  - Challenges faced and their solutions

- CMS High granularity calorimeter (HGCAL)
  - Design and prototyping

- Summary

# Purpose of Belle II

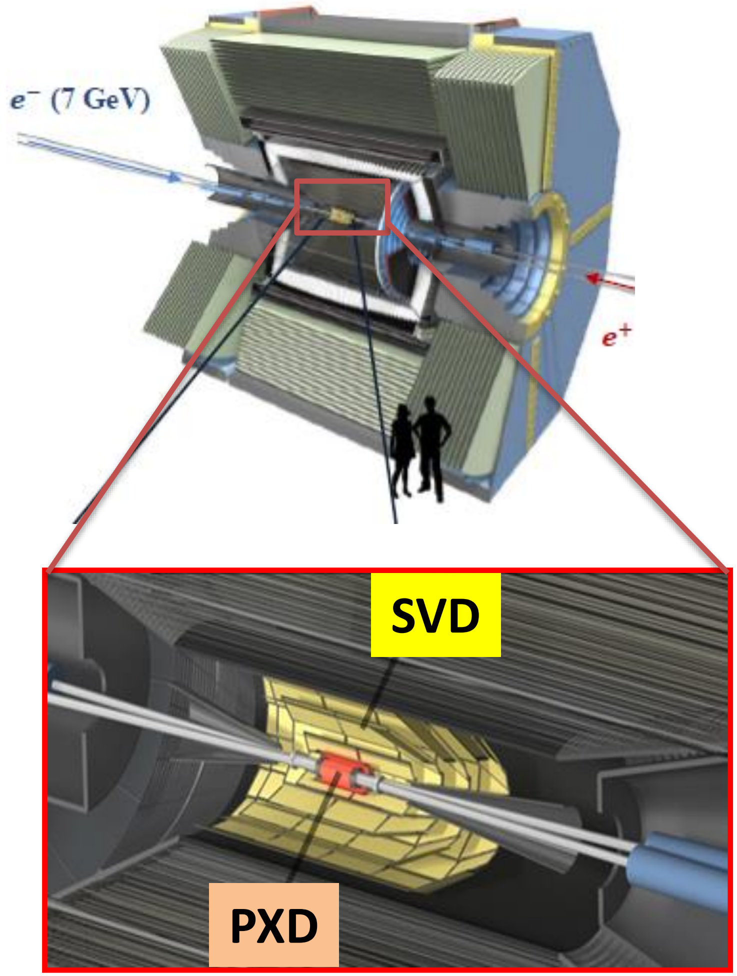
Belle II, the 2nd generation flavor factory experiment, is designed to make precise measurements of weak interaction parameters and through that, to indirectly probe physics beyond the Standard Model of particle physics.

Vertex Detector is a key element of the experiment in this pursuit.

# Belle II Vertex Detector (VXD)

- **Determine the vertex position of subatomic particles**
- **Measure the two-dimensional track position and momentum for charged particles**

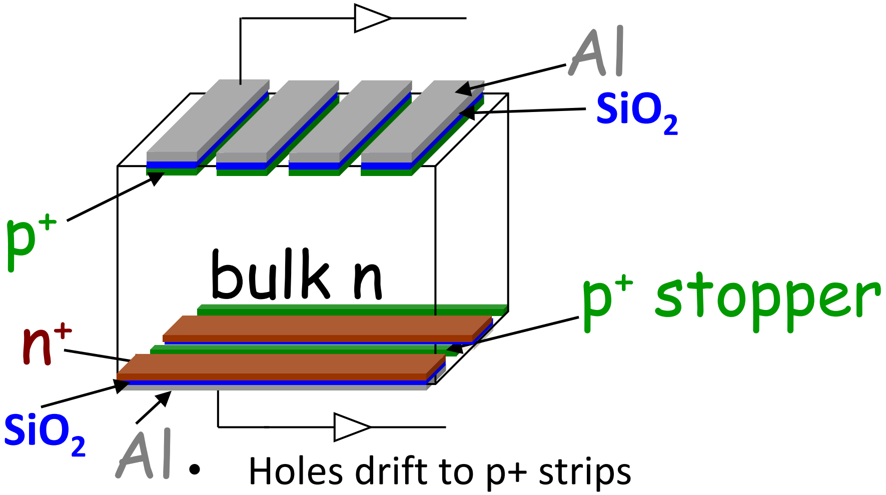
- PiXel Detector (PXD)
- Silicon Vertex Detector (SVD)
  - Double-sided silicon strip detectors (DSSDs)



## VXD requirements

- Operate in high rate environment
- Must have excellent spatial resolution
- Be radiation hard (up to 10 Mrad)
- Good tracking capability – to track particles down to 50 MeV in $p_T$ and help in particle identification

**DSSD:**



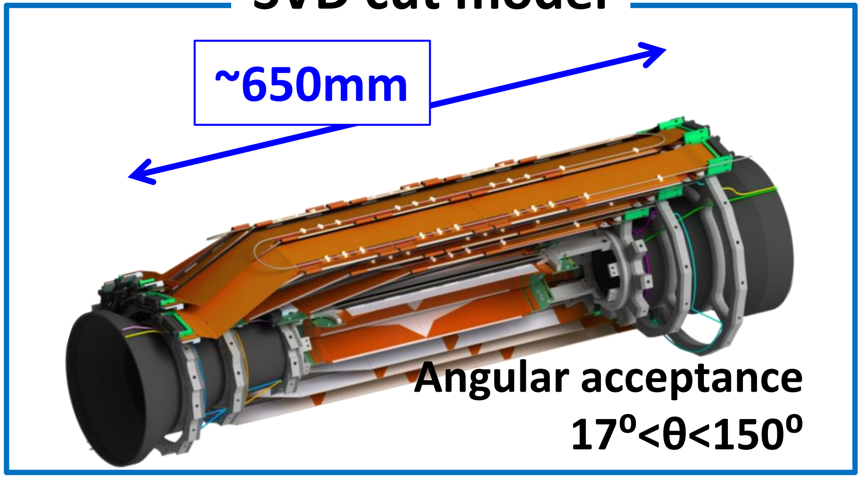
- Holes drift to p+ strips
- Electrons drift to n+ strip

**One MIP produces about 24k electrons**

# SVD Ladder Layout

**Each ladder consists of a number of DSSDs along with requisite readout electronics**

**SVD cut model**

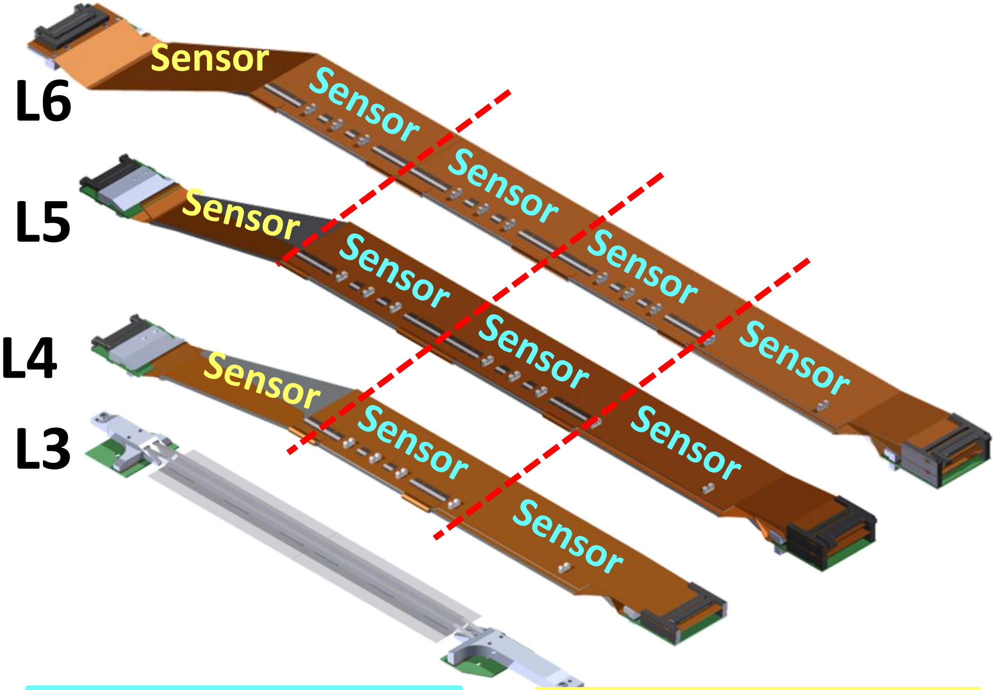


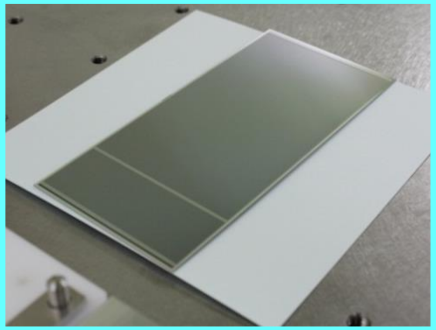
**Angular acceptance**
**17°<θ<150°**

**Forward**

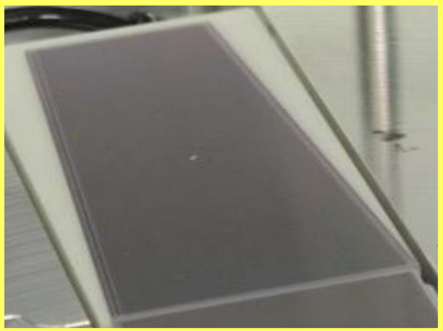
$R_{L3}$ = 38mm $R_{L5}$ = 115mm
$R_{L4}$ = 80mm $R_{L6}$ = 140mm

| Layer | Institute |
|---|---|
| 3 | University of Melbourne |
| 4 | TIFR Mumbai (10 + 2 spares) |
| 5 | HEPHY Vienna |
| 6 | IPMU University of Tokyo |
| FW & BW subassemblies (L4-L6): INFN Pisa | |





**Rectangular sensor**

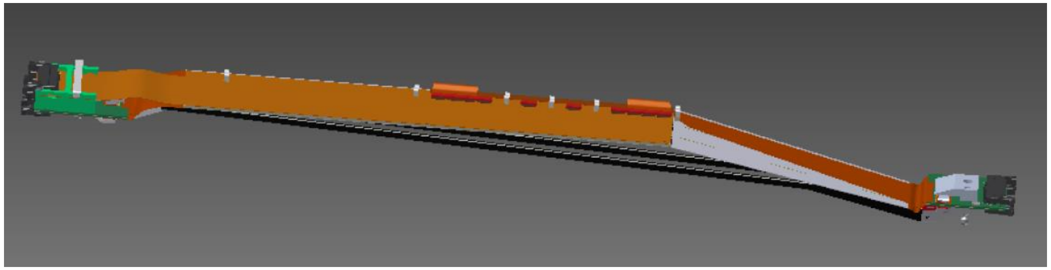


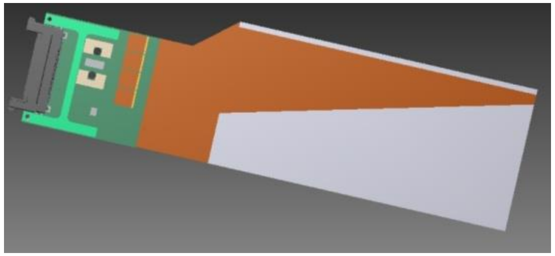
**Trapezoidal sensor**

# L4 Ladder: 3D Model

## Components of Ladder :

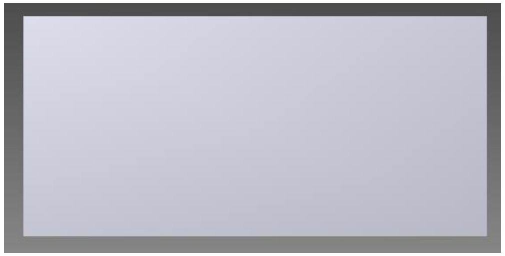
- Rectangular double sided silicon sensor
- FW and BW sub assembly
- Ribs = 2 numbers -- made from carbon fiber (light in weight, stiff, low material budget)
- Forward and Backward endmounts with silpad and Keratherm
- FW and BW kokeshi pins
- Prism rail
- FW an BW APV guards
- Airex
- Origmai –Z
- $CO_2$ clamps
- H shape





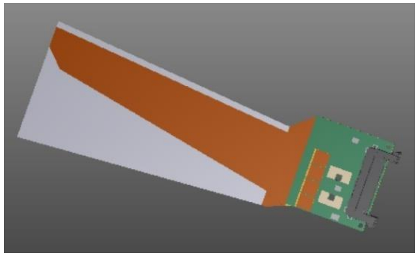
Backward sensor

Sensor : 124.88 x 59.6 x 0.32mm



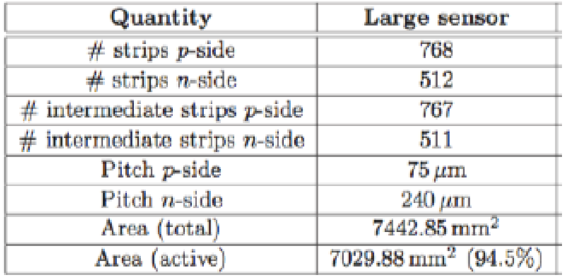
Central sensor

Sensor : 124.88 x 59.6 x 0.32mm



Forward sensor

125.96 x 60.63/41 x 0.3mm

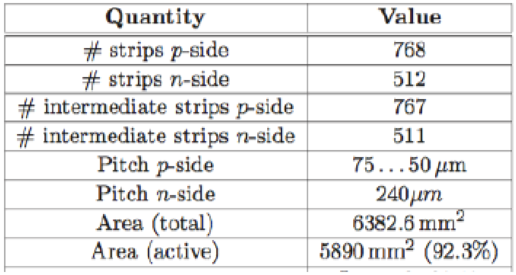


| Quantity | Large sensor |
|---|---|
| # strips $p$-side | 768 |
| # strips $n$-side | 512 |
| # intermediate strips $p$-side | 767 |
| # intermediate strips $n$-side | 511 |
| Pitch $p$-side | 75 $\mu m$ |
| Pitch $n$-side | 240 $\mu m$ |
| Area (total) | 7442.85 $mm^2$ |
| Area (active) | 7029.88 $mm^2$ (94.5%) |

Gap between sensors

BW and Central sensor 120µm

FW and Central sensor 394µm



| Quantity | Value |
|---|---|
| # strips $p$-side | 768 |
| # strips $n$-side | 512 |
| # intermediate strips $p$-side | 767 |
| # intermediate strips $n$-side | 511 |
| Pitch $p$-side | $75 \ldots 50\,\mu m$ |
| Pitch $n$-side | $240 \mu m$ |
| Area (total) | 6382.6 $mm^2$ |
| Area (active) | 5890 $mm^2$ (92.3%) |

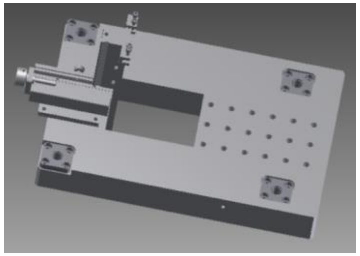
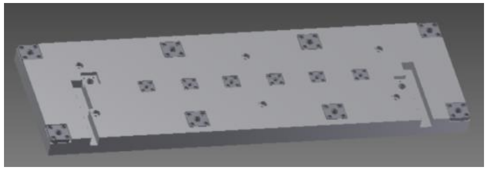
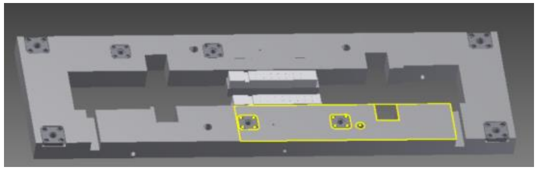
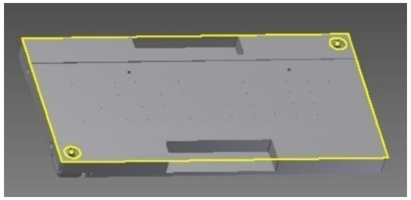
# How to assemble the SVD ladders?

- Need a clean room & several expensive equipment
- Precise placement of each component is crucial
- Need mechanical fixture or ‘jigs’ to accomplish that
- Development of 3D modeling of jigs
- 2D conversion along with tolerance
- Jigs produced

- Verification of jigs using a CMM
- Fine tuning of the produced jigs
- Gluing of components with a gluing robot
- Wirebonding of sensors, PAs and readout chips
- Mechanical precision measurement using the CMM
- Electrical testing of the ladder

# 3D modeling and production of jigs

1) Autodesk Inventor Professional 2012 – learned the software from scratch to design the jigs required

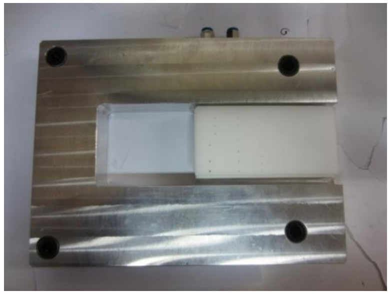
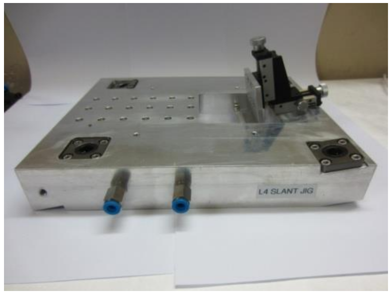





Some of the jigs 3D models ~ 30 numbers

2) Some of the produced jigs

Material used for jigs:  Aluminum alloy 6061 and  Polyacetal


Assembly bench – 650x200x30mm

Baseplate for wirebonder

Jig for gluing robot

Length of rods tolerance : +/- 40 µm
Diameter of rods : +/-20 µm
Flatness of small jigs :  less than 70 µm
Flatness of large jigs  :   less than 150 µm

Production of the jigs and their CMM were performed at our workshop

# Joint assembly center for L4 and L6 ladders

**Kavli Institute for the Physics and Mathematics of Universe (IPMU), University of Tokyo, Kashiwanoha, Japan**

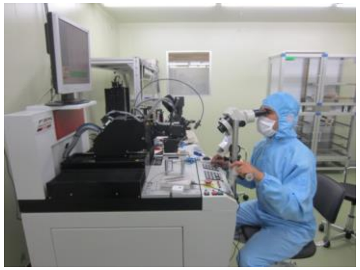
- APV readout chip import restrictions
- Funding issue

**Advantages:**

- Sharing of resources
- Excellent environment for ladder assembly
- Easy for transportation of Ladder to KEK

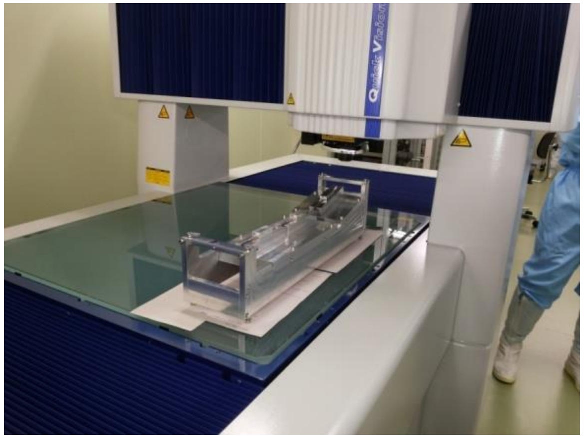
# Key steps and instruments for ladder assembly

- SPA ( Sensor with Pitch Adapter) production
- Rib Assembly
- FW and BW testing
- Half ladder assembly
- Origami assembly
- Full ladder assembly
- Mechanical precision measurement
- Electrical quality assurance



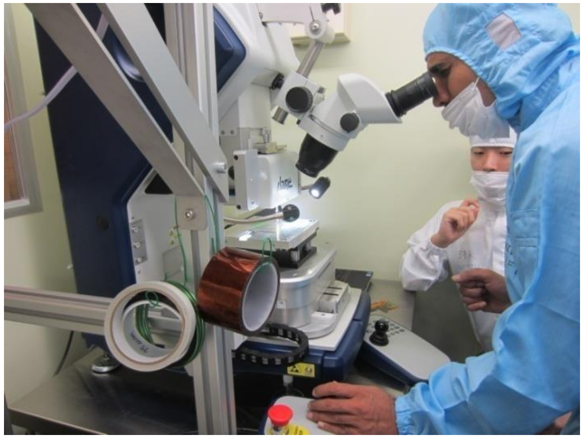
Wire Bonder (TIFR)

Microscope (TIFR)



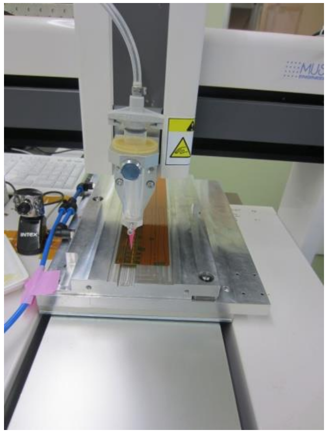
Coordinate Measuring Machine (CMM) - IPMU

Gluing Robot (IPMU)



Pull Tester (IPMU)

# Gluing procedure and optimization



Musashi ShotMaster Gluing robot

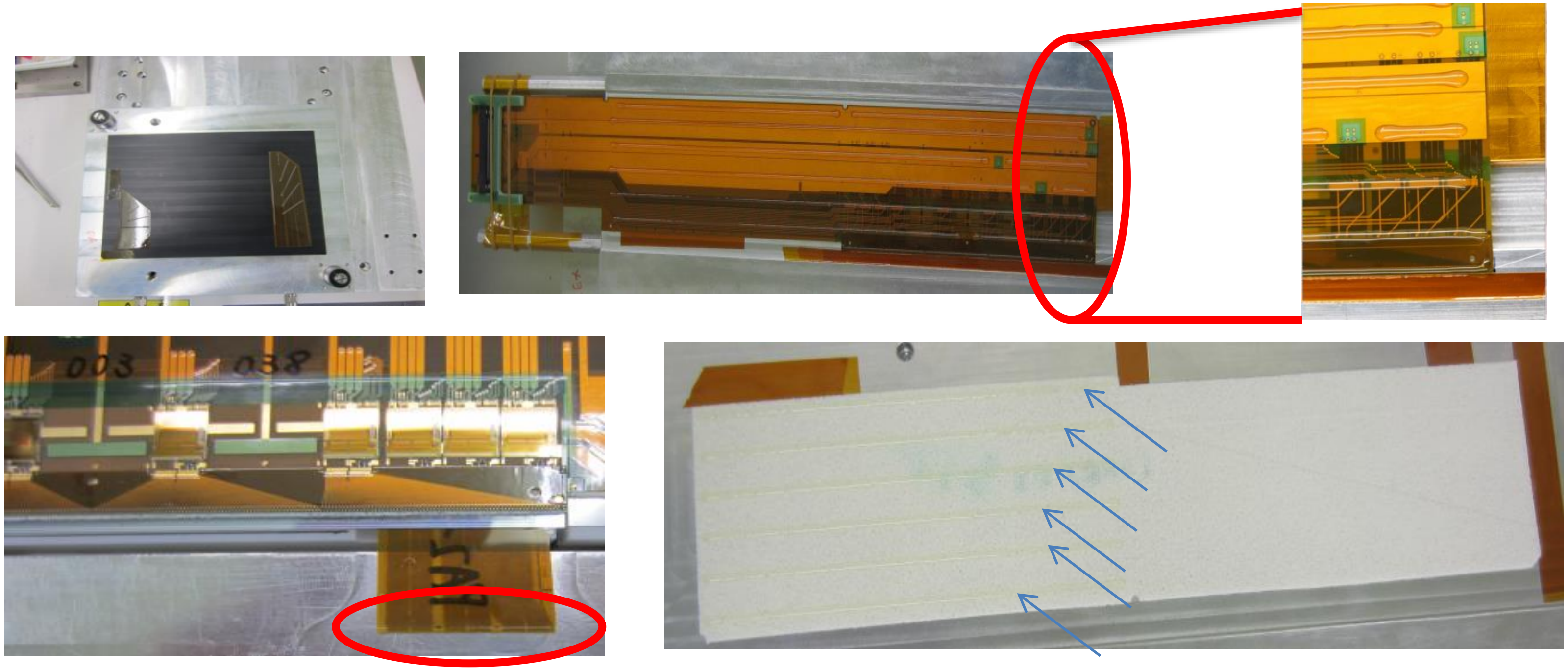
Programs were developed for each application

1) PA1 and PA2 jig
2) Airex jig
3) Origami jig
4) Assembly bench jig

Araldite 2011

More Glue - it will overflow on the pads
Less Glue - difficult to perform wirebond on the corresponding pads
Bubbles formation in the glue while dispensing - we can not bond at that location

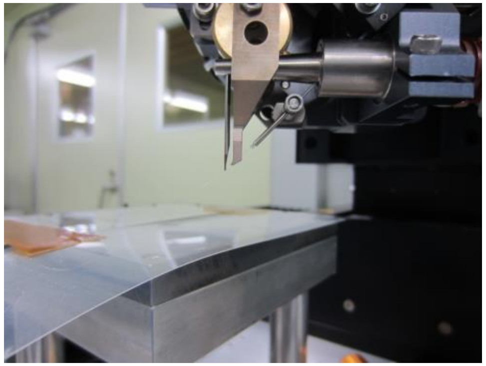
We have to optimize the speed , distance and height of the syringe to get good results



Glue pattern on different components

# Wirebonding and Pull testing

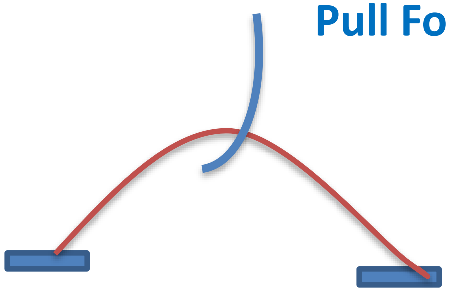
Delvotec 6400 Wirebonder



Wire : Al Si (1%), 25µm diameter

Tool Hole size = 38µm

Dage 4000 Plus -- Pull Tester



Pull testing of a bonded wire

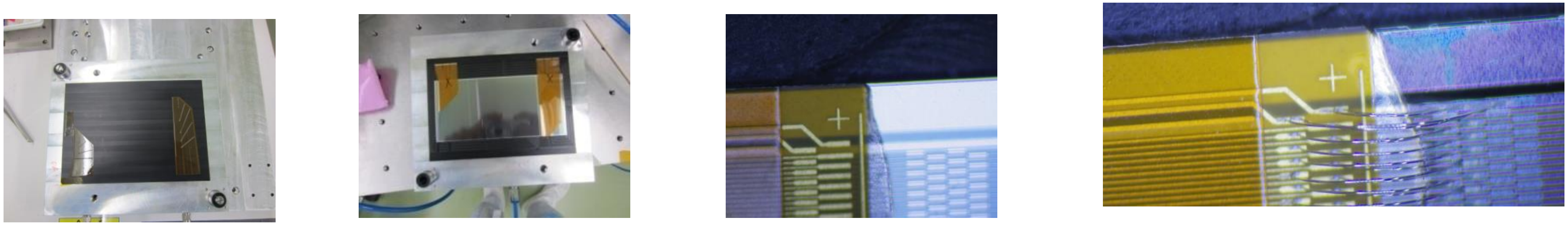
| Pull Strength ( gm f ) | Wire broke at |
|---|---|
| 9.78 | Pitch adaptor |
| 11.72 | Sensor |
| 11.19 | Sensor |
| 9.34 | Pitch adaptor |
| 11.26 | Pitch adaptor |
| 10.57 | Pitch adaptor |
| 10.68 | Pitch adaptor |
| 11.68 | Sensor |
| 11.34 | Pitch adaptor |
| 10.86 | Pitch adaptor |
| 11.16 | Pitch adaptor |
| 11.63 | Sensor |

Average pull strength = 11.0 gm f

Average pull tests per sample = 100

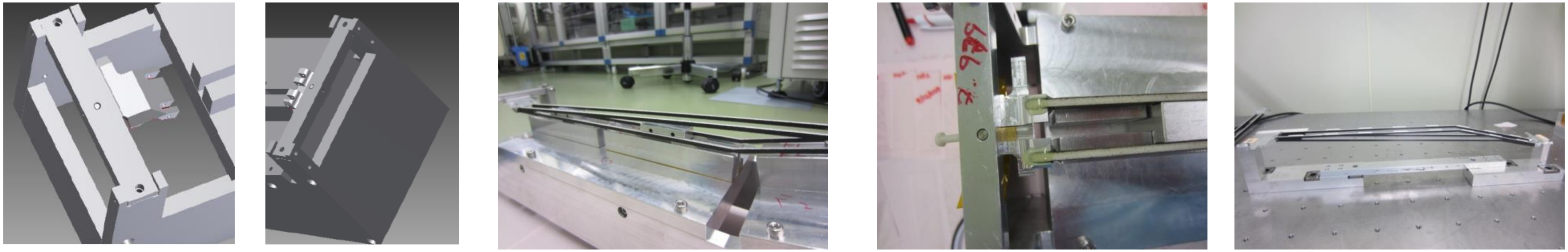
# SPA and Rib Assembly

## SPA production



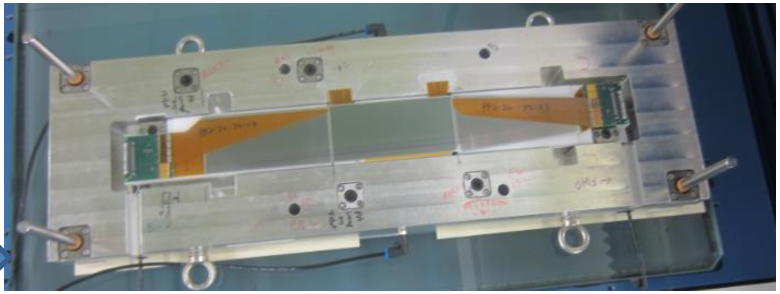
Wirebonds - PA1 - 192x2,pitch 150µm
( Total :768) PA2 - 192x2,pitch 150µm
Bias bonds - 4 for each
Automatic programming

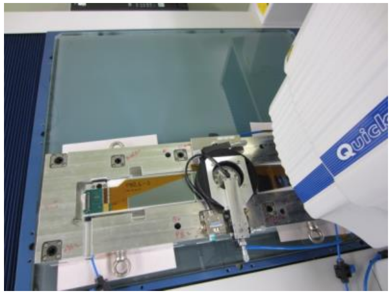
## Rib Assembly



# Half Ladder

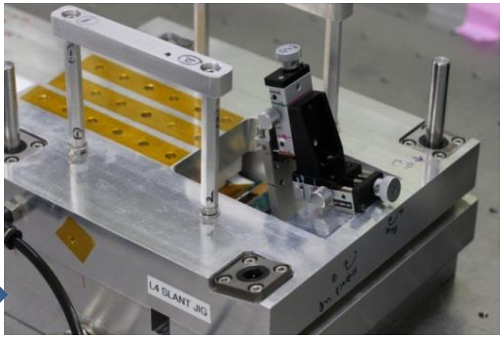
- Place SPA
- Test, pickup and place SFW
- Test, pickup and place SBW


All sensors on the assembly bench

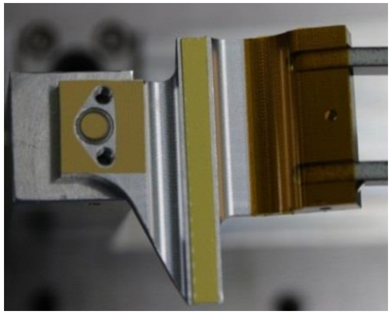


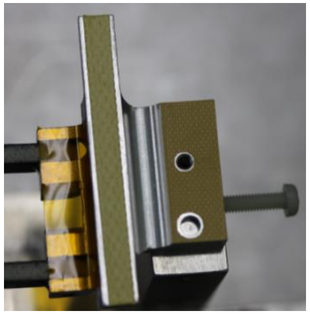
Fine tuning each sensor position

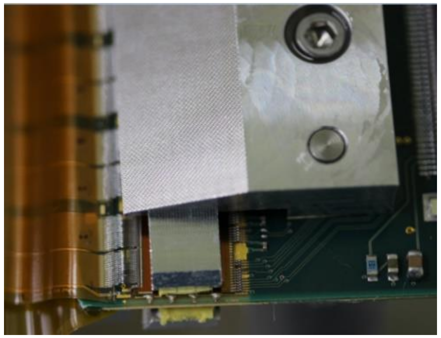
- Pickup FW sensor along with hybrid board
- Pickup BW sensor along with hybrid board

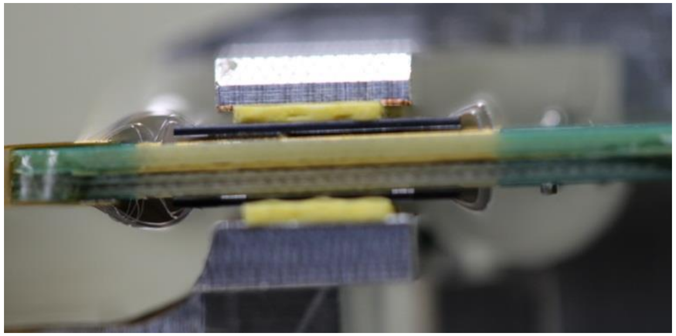


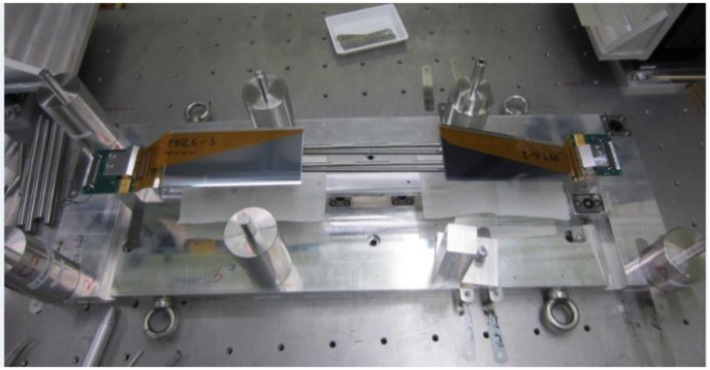
Slant Jig- to hold sensor and hybrid board


BW endmounts for Keeping hybridboard

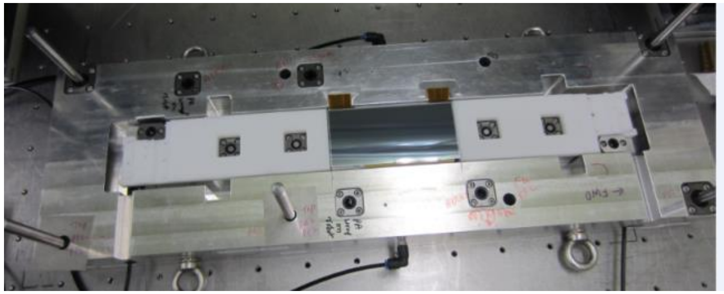

FW endmounts for Keeping hybridboard


Top view after placing APV guard in FW

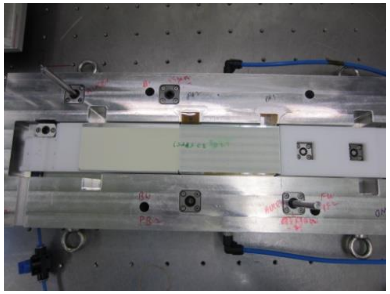

Side view after APV guard placing


Half Ladder

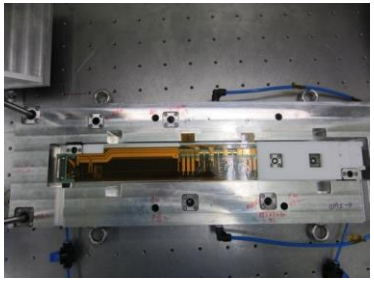
# Origami sub-assembly



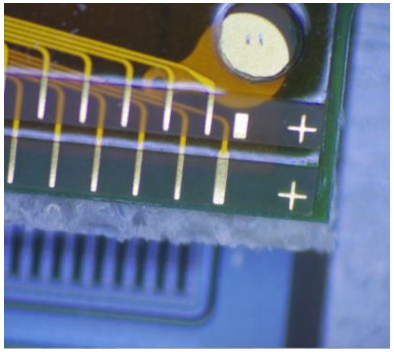
SPA on assembly bench



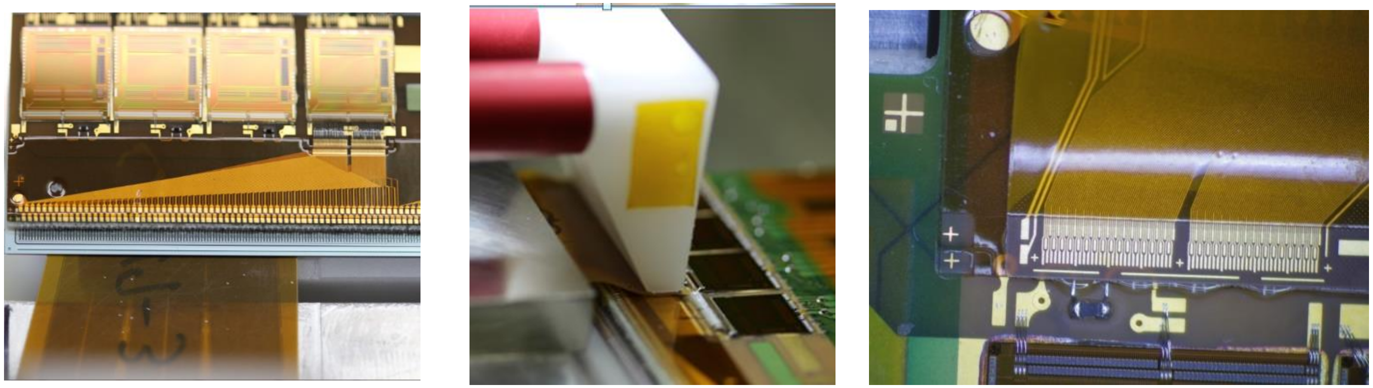
Airex placed



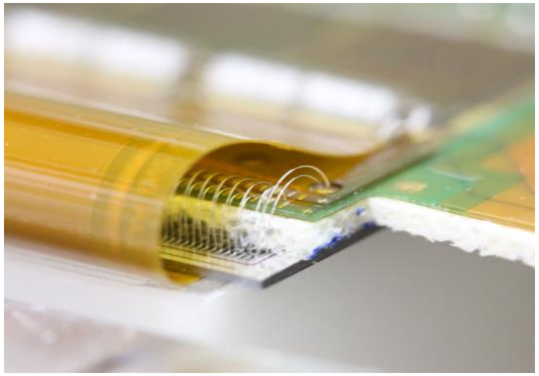
Origami placed



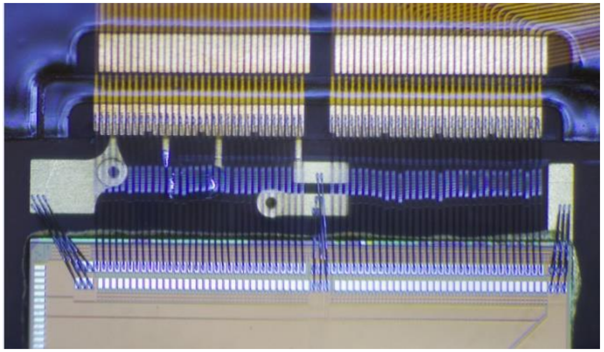
Close view location



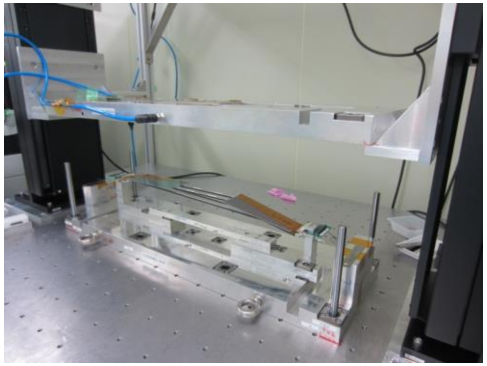
Pitch adapter wrapping procedure



After wrapping

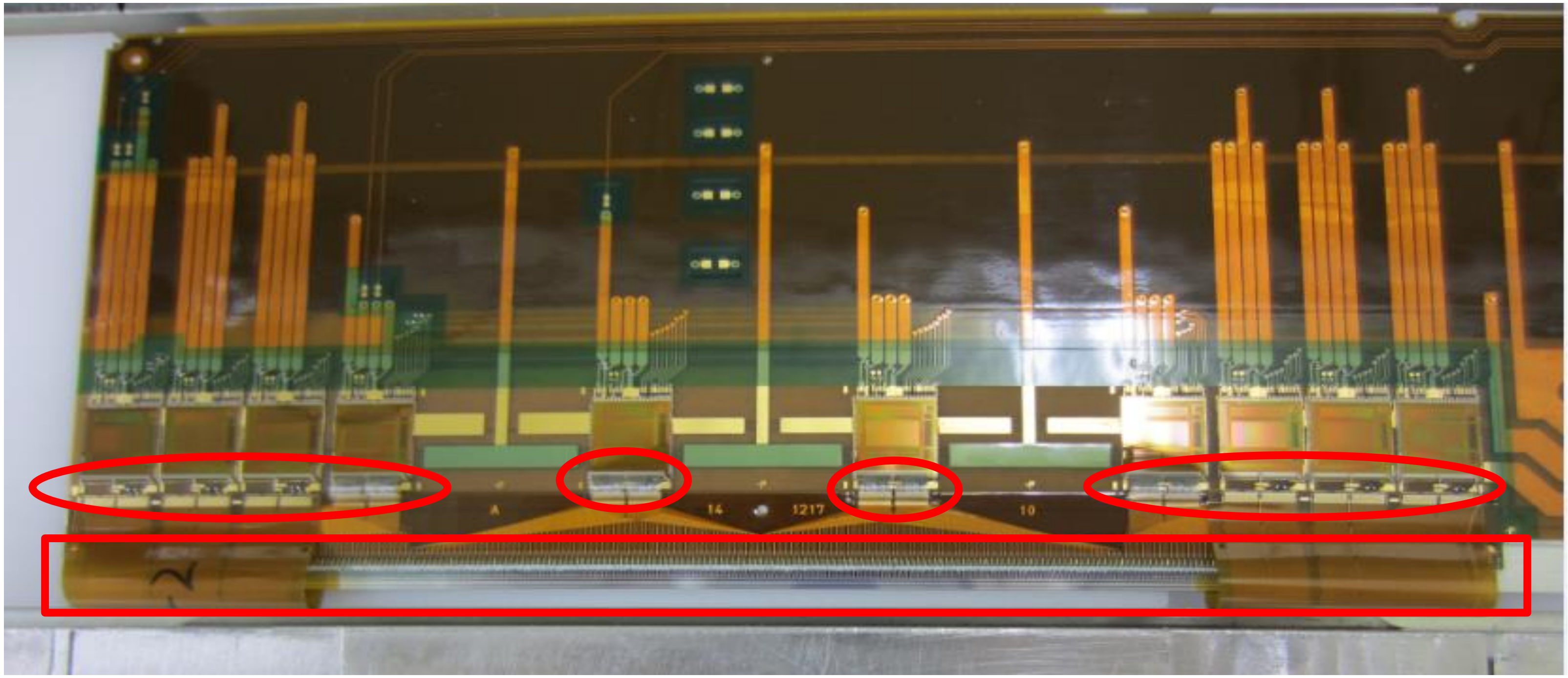


APV chip wirebonding



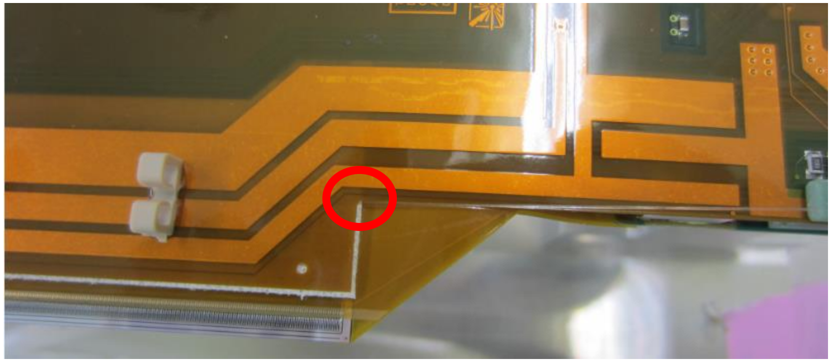
Half ladder + origami installation

# Wirebonding at different locations



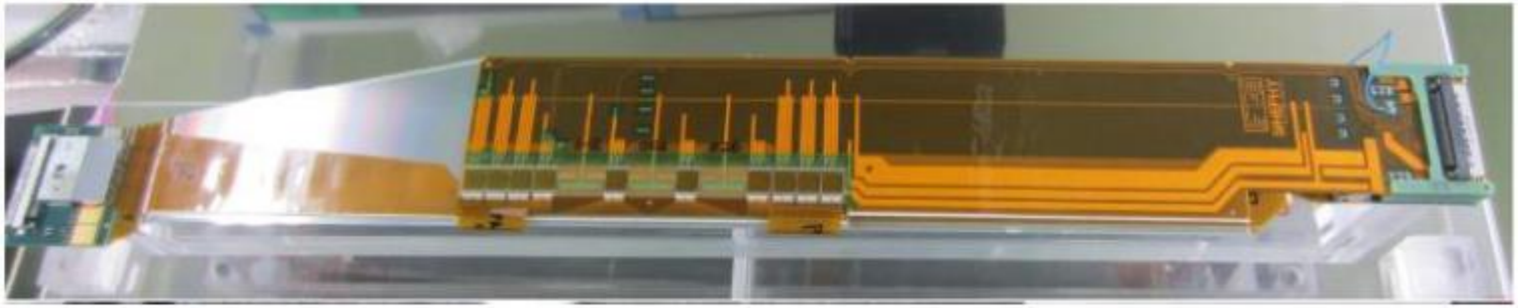
Origami module

Sensor with PA

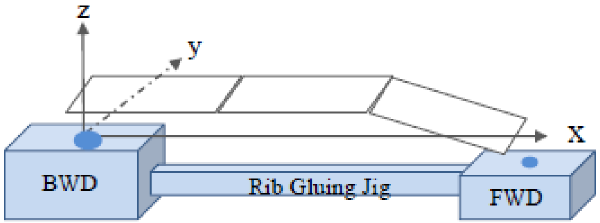


Fiber optic insertion testing

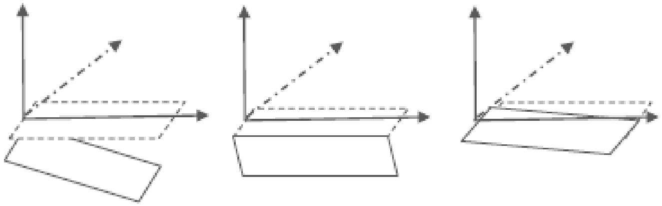
# Mechanical precision measurements



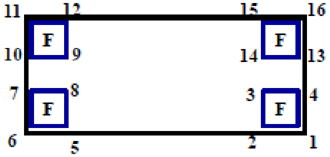
Fully assembled L4 ladder



Ladder Coordinate Frame (L4)



Slant, tilt and rotation angles



'F' are Measurement marks on sensors

**Survey Results : Translational and Rotation parameters**

Displacement of the DSSD sensors in XY directions w.r.t. nominal position should be less than 150 $\mu$m and in Z direction should be less than 250 $\mu$m.

Slant angle: Design requirement is 11.9 degree for FW sensor and 0 degree for CE and BW sensors.

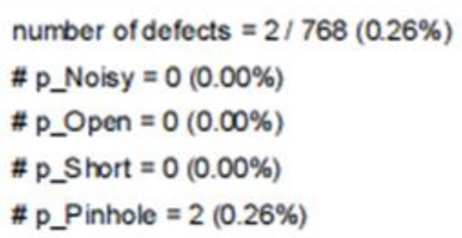
Tilt and rotational angle: Design requirement is 0 degree for all sensors.

| Sensor | Δx ($\mu$m) | Δy ($\mu$m) | Δz ($\mu$m) | Slant angle | Tilt angle | Rotation angle |
|---|---|---|---|---|---|---|
| L4 Forward | -72.3972 | -10.1284 | 79.7179 | -11.9384 ± 0.0051 | -0.0280 ± 0.0118 | -0.0229 +- 0.01 |
| L4 Origami-Z | 12.5750 | -39.0695 | -26.2813 | -0.0544 ± 0.0008 | 0.0639 ± 0.0017 | -0.0279 +- 0.01 |
| L4 Backward | - 63.8592 | -36.3776 | 1.09204 | -0.0042 ± 0.0025 | -0.0007 ± 0.0053 | -0.0863 +- 0.01 |

**Similar results were obtained for all assembled L4 ladders**

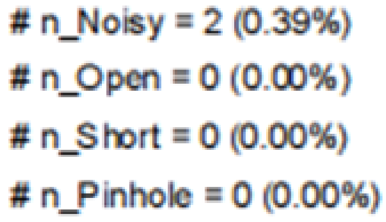
# Electrical test results and installation

P side



number of defects = 2 / 768 (0.26%)
# p_Noisy = 0 (0.00%)
# p_Open = 0 (0.00%)
# p_Short = 0 (0.00%)
# p_Pinhole = 2 (0.26%)

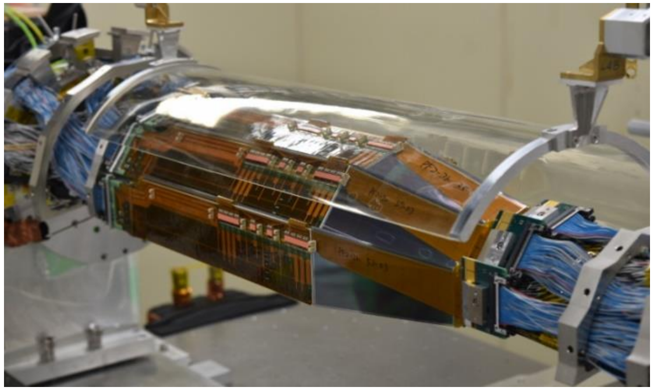
N side



# n_Noisy = 2 (0.39%)
# n_Open = 0 (0.00%)
# n_Short = 0 (0.00%)
# n_Pinhole = 0 (0.00%)

**No electrical defects introduced during assembly**

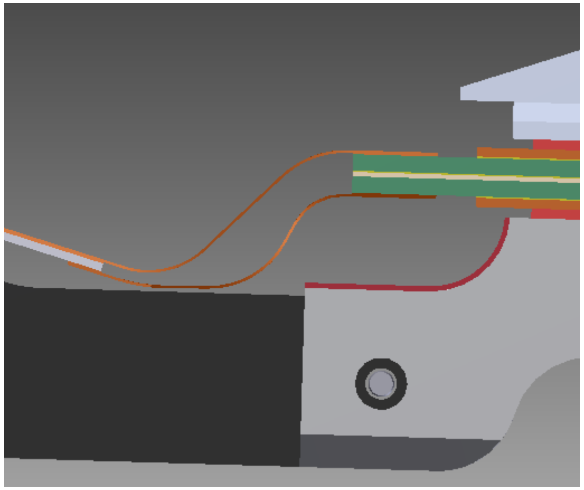
- Prepared a manual and followed a step-by-step procedure to avoid any mistakes or missing items that are well defined and reproducible
- Updating the data in the database
  1) All components are given suitable number to identify
  2) Day-to-day update with checklist of the work done on a given day
  3) Upload the electrical test data as well as photo’s taken at critical locations



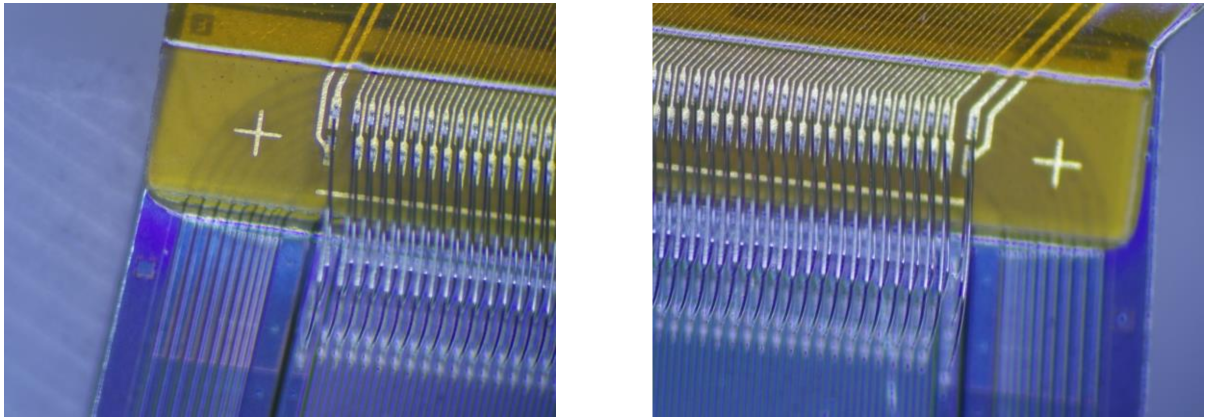
**L4 Ladders installed**

**All Ladders are installed**

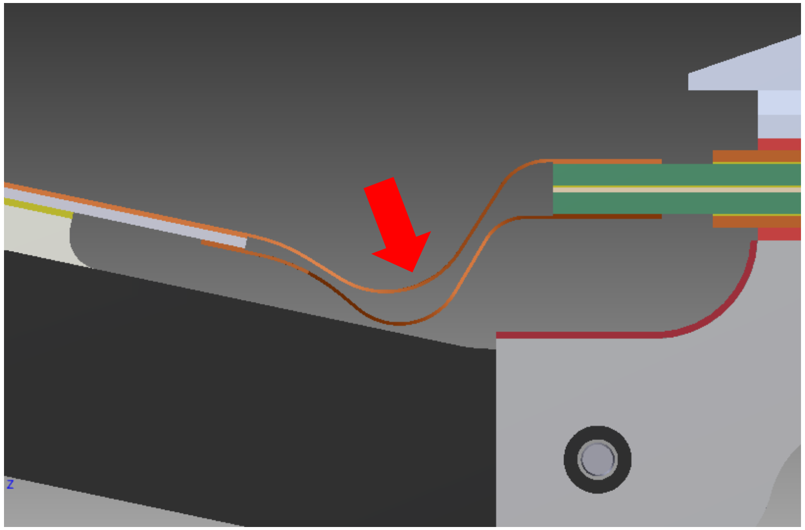
# Design issue in forward sensor



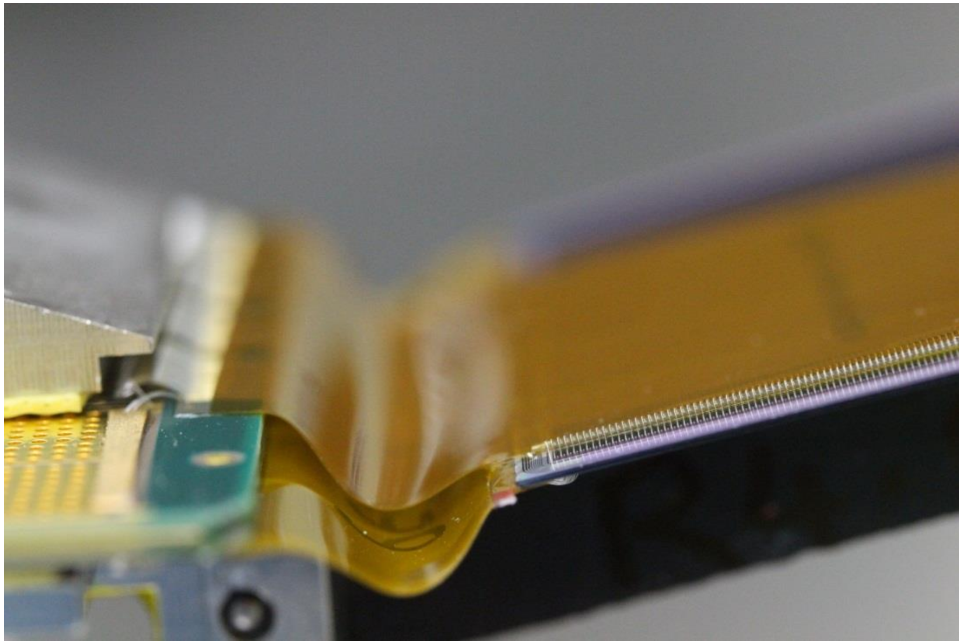
Pitch adapter shape – 3D model – L5



Sensor and pitch adapter glued and wirebonded before placing on the ribs

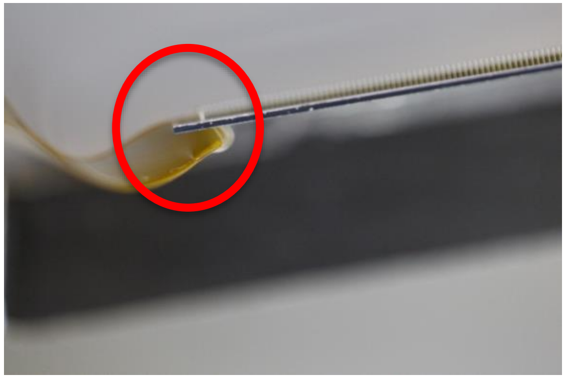


Pitch adapter shape – 3D model – L4



Pitch adapter shape after assembly

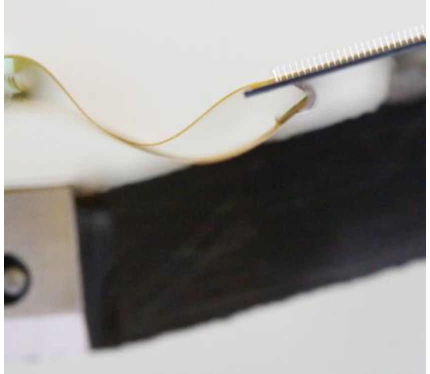
# 1. First peel-off issue



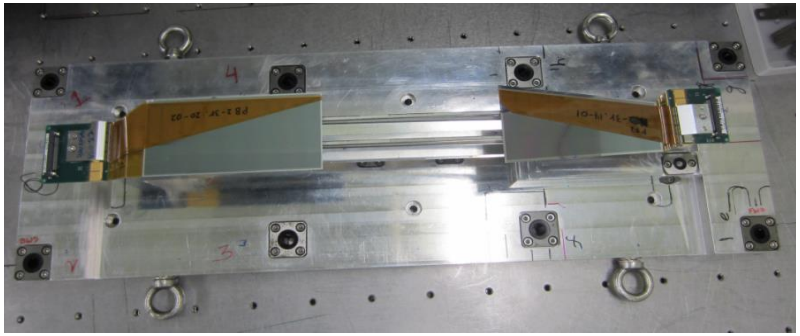
- Observed during ground wire soldering in the SFW after assembly of full ladder

- Peel-off happened first time during the class A ladder Assembly in L4 only

**Discard this Ladder**

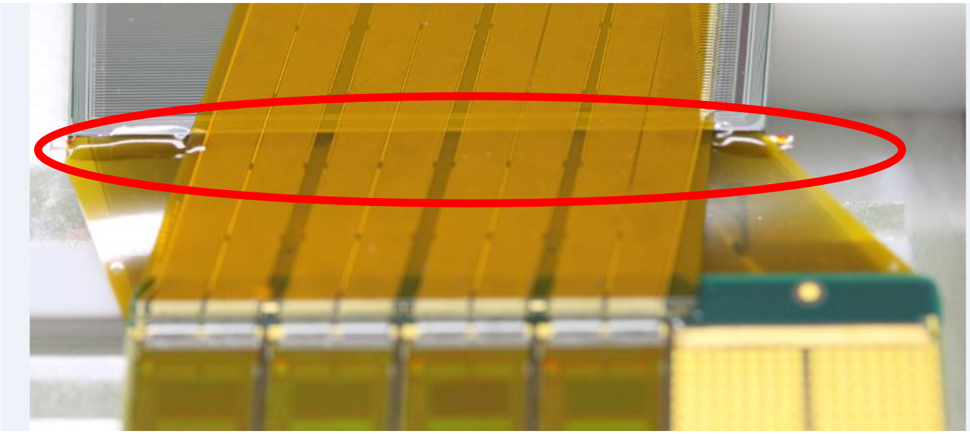


Peel off in the half ladder



**Discarded half ladder**

Half ladder

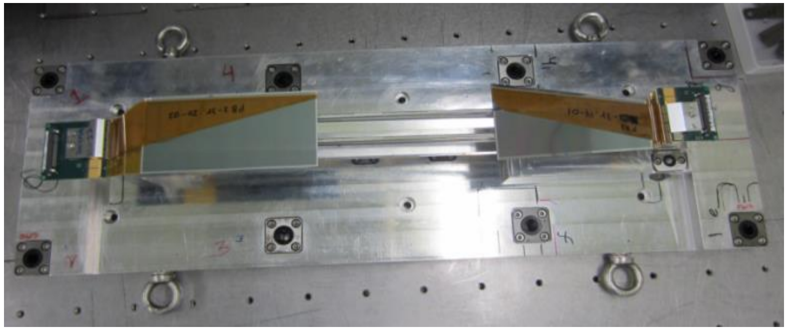


To avoid Peel-off issue :

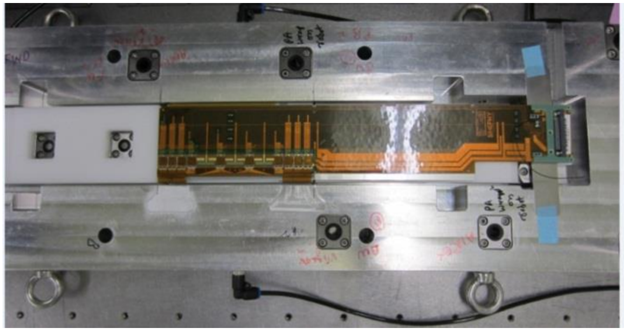
- Reinforcement with Mylar sheet along with glue on FW subassembly before placing it on the half ladder

# 2. New jig designed owing to peel-off

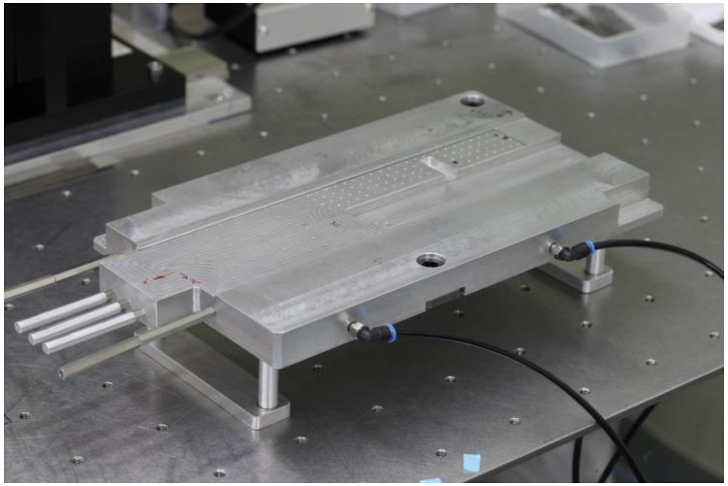
**Half Ladder**



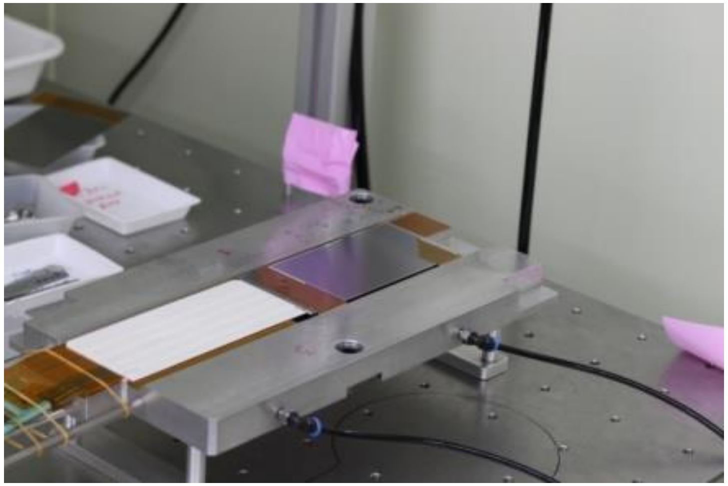
**Origami –Z module**



- We follow standard sequential procedure during module assembly
- Not expected this type of peel off problem
- Kept the origami –Z module on the assembly base and designed and produced pickup jig
- Produced jig was used to pickup the origami –Z module to make a way for aligning the FW and BW subassemblies on the assembly bench and glue on to the ribs

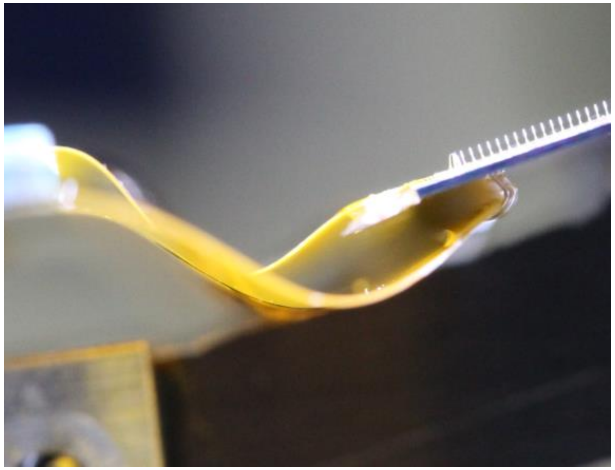


Origami Pickup Jig



Origami Pickup Jig with the origami module

# 3. Second peel-off issue in half ladders



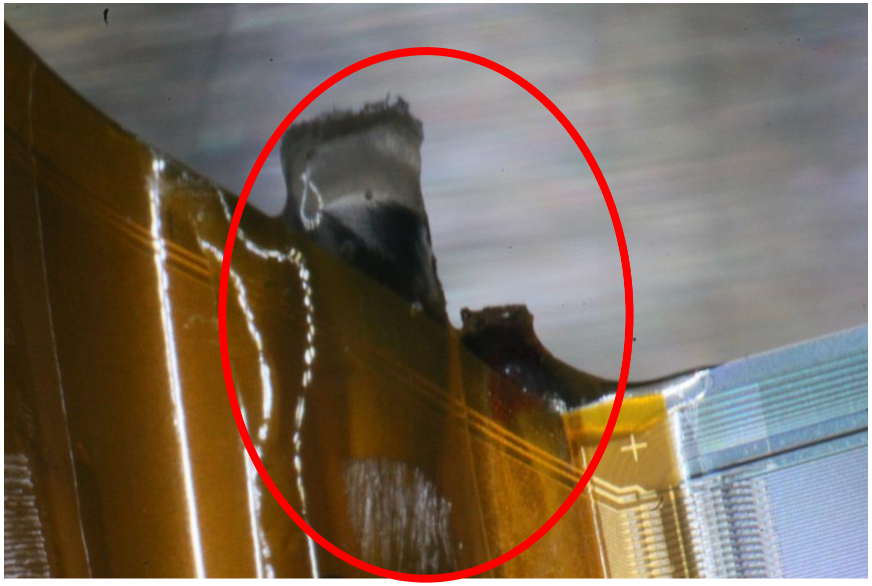
Peel off in the half ladder

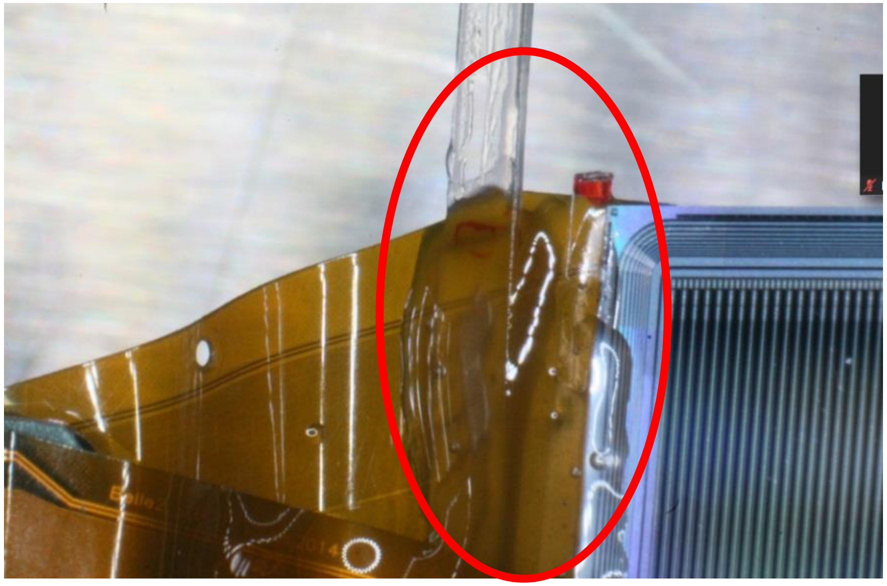
Later the same peel off observed in L6 in full and half ladders. After this we suspended the ladder assembly which was disturbing our ladder assembly schedule

Solution : Two Mylar pieces - Successful

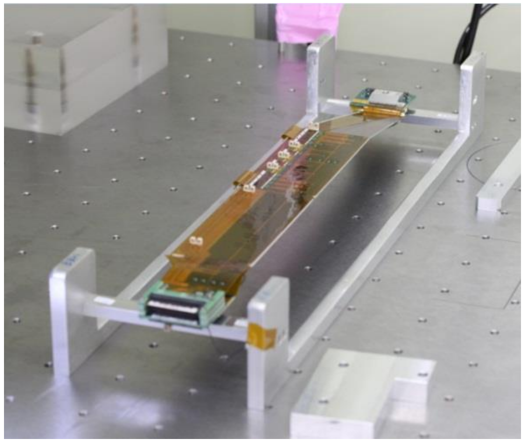
**Precaution :** Prepare half ladders and keep it for two week to identify any peel off issues

Discarded half ladder

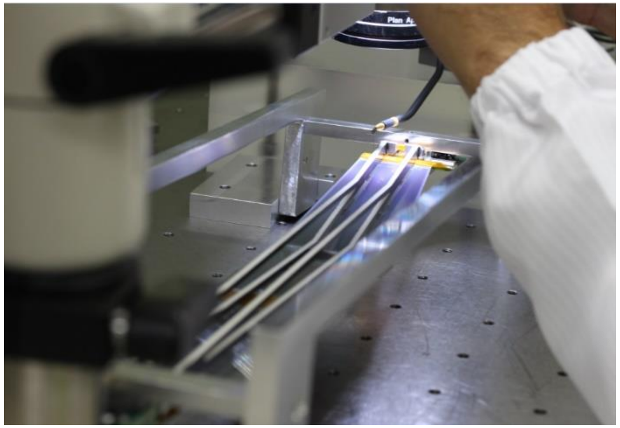




# 4. Removing wirebonds of suspicious behavior



Ladder rested on **flip jig**

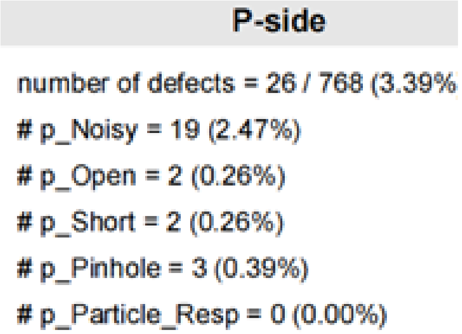


Pulling the problematic wirebond

New Jig Developed
for this application – **Flip jig**

# 5. Noisy strips issues in one of the ladders

- OS4.009 - Noisy strips appeared after wirebonding - suspicious wirebonds are removed
- Due to large number of defects, proposed to keep it aside for the time being
- Designing a new jig for the storage of OS4.009



**P-side**

number of defects = 26 / 768 (3.39%

# p_Noisy = 19 (2.47%)

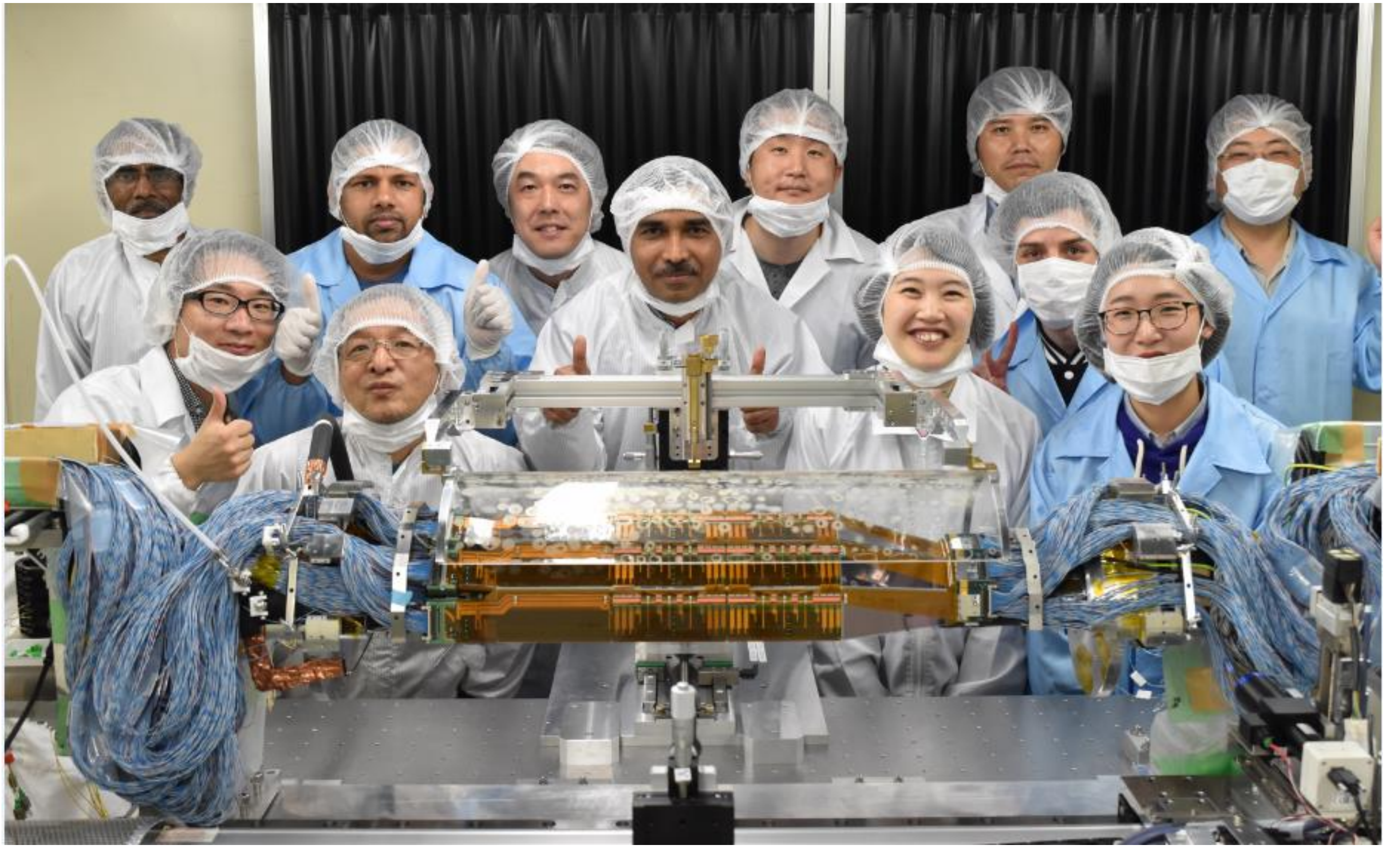
# p_Open = 2 (0.26%)

# p_Short = 2 (0.26%)

# p_Pinhole = 3 (0.39%)

# p_Particle_Resp = 0 (0.00%)

# L4, L6 and ladder mount teams from KEK



**L4 team**

**Assembly: TIFR (Scientific, technical staff, students and postdocs) , IIT Madras (Student)**

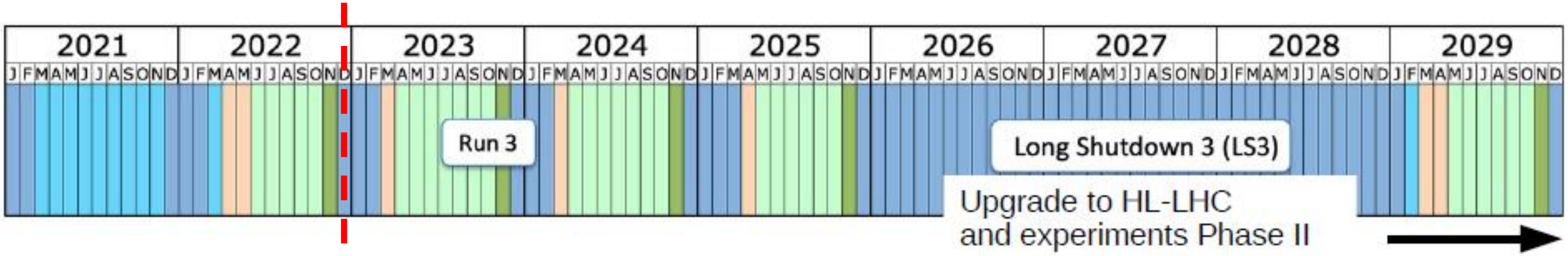
**Installation: TIFR, IIT Hyderabad and Madras**

# LHC upgrade to High Luminosity LHC

| | | | |
|---|---|---|---|
| Luminosity: | $2.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ | → | $(5.0 – 7.5) \times 10^{34}$ cm$^{-2}$s$^{-1}$ |
| Pileup events: | O(80) | → | O(140-200) |
| Radiation: | $10^{14}$ $n_{eq}$/cm$^2$ | → | $(1.0 – 1.5) \times 10^{16}$ $n_{eq}$/cm$^2$ |

More radiation, more pileup, higher density of tracks, more data…..

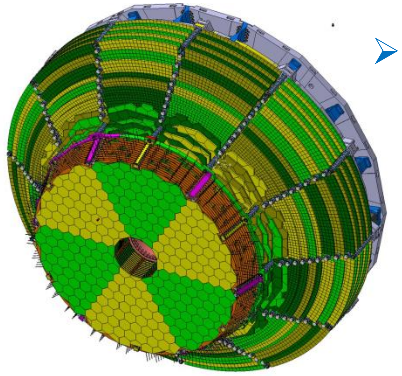
Existing CMS detector will not survive through HL-LHC, necessitating the upgrade for most of its subdetectors in order to cope up with the above challenges

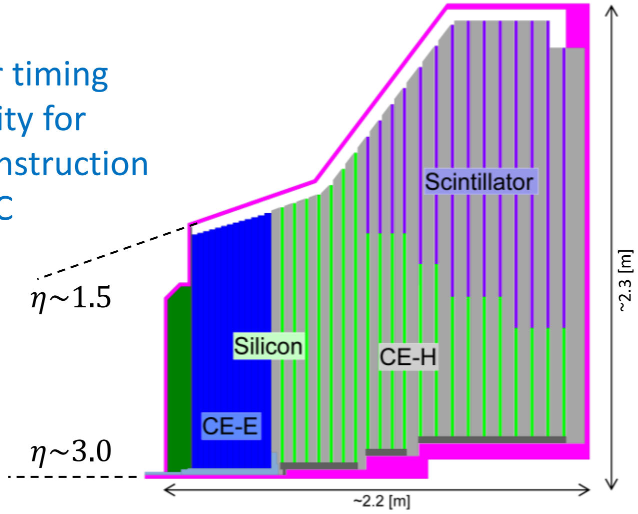


Upgrade to HL-LHC and experiments Phase II

- **CMS endcap calorimeters will be replaced by a high-granularity calorimeter (HGCAL)**

  - ➢ Radiation tolerant
  - ➢ High granularity
  - ➢ Precise hit/cluster timing
  - ➢ Enhanced capability for particle flow reconstruction
  - ➢ Operation at -30°C





**CE-E (Electromagnetic)**
Active: Silicon
Passive: Cu, CuW, Pb absorbers
13 double-sided layers (full silicon)

**CE-H (Hadronic)**
Active: Silicon + Scintillator / Silicon-photomultiplier
Passive: Steel absorbers
21 Silicon layers (full + mixed)

# Why HGCAL?

- Need to improve the jet resolution for the next generation of calorimeters
- At high jet energy, correct association between the tracks and calorimetric clusters is crucial, so going for calorimeter with very high granularity

**To realize a high-granularity calorimeter (HGCAL), we need:**
low cost/area active material(s), radiation-tolerant on-detector electronics, high-bandwidth data transmission, and powerful FPGAs for off-detector electronics

**A largely silicon-sensor-based calorimeter**

# Technical requirements of HGCAL

**Planar p-type DC-coupled sensor pads**

- simplifies production technology; p-type more radiation tolerant than n-type

**Hexagonal sensor geometry preferred to square**

- makes most efficient use of circular sensor wafers
- reduces the number of sensors to be produced or assembled into modules

**8” wafers preferable to 6”**

- reduces the number of sensors produced or assembled into modules
- cost per unit area is cheaper and simplifies the module mechanics

**300 μm, 200 μm and 120 μm active sensor thicknesses**

- match sensor thickness (and granularity) to radiation field for optimal performance

**Simple, rugged module design & automated module assembly**

- provides high volume, high rate, reproducible module production & handling
- ~5K Silicon-detector modules need to be assembled in India (~15 modules per day capacity) for total requirement of ~26K HGCAL modules

| **8” Low-Density sensor** | **8” High-Density sensor** |
|---|---|
| 192 cells with ~1.26 Sq.cm size | 432 cells with ~0.56 Sq.cm size |
| 300μm & 200μm active thickness | 120μm active thickness |

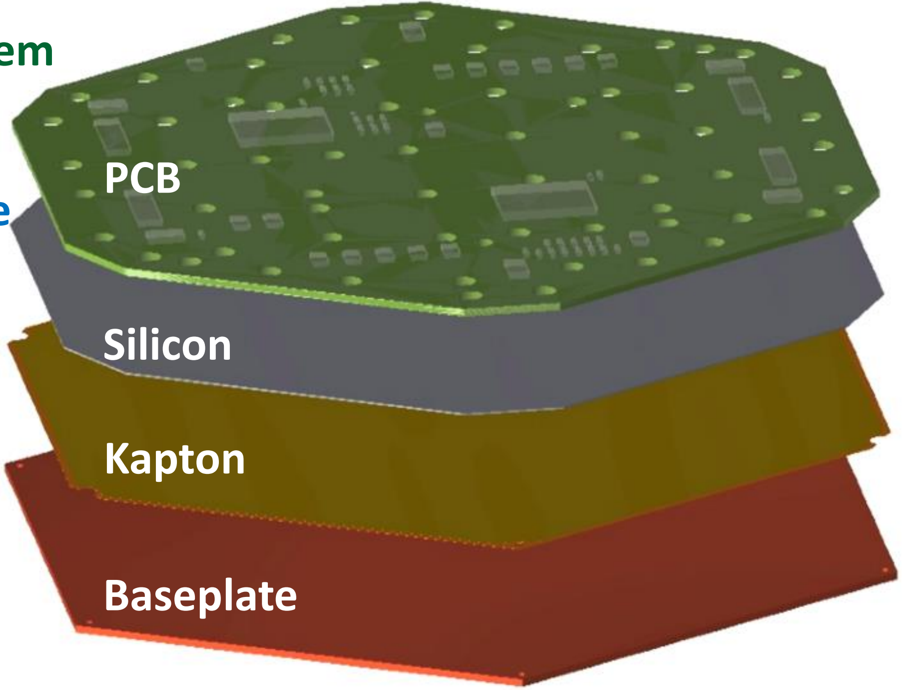
# HGCAL module requirement

**Key steps involved:**

- Gluing
- Wire bonding
- Visual inspection
- Electrical testing
- Encapsulation

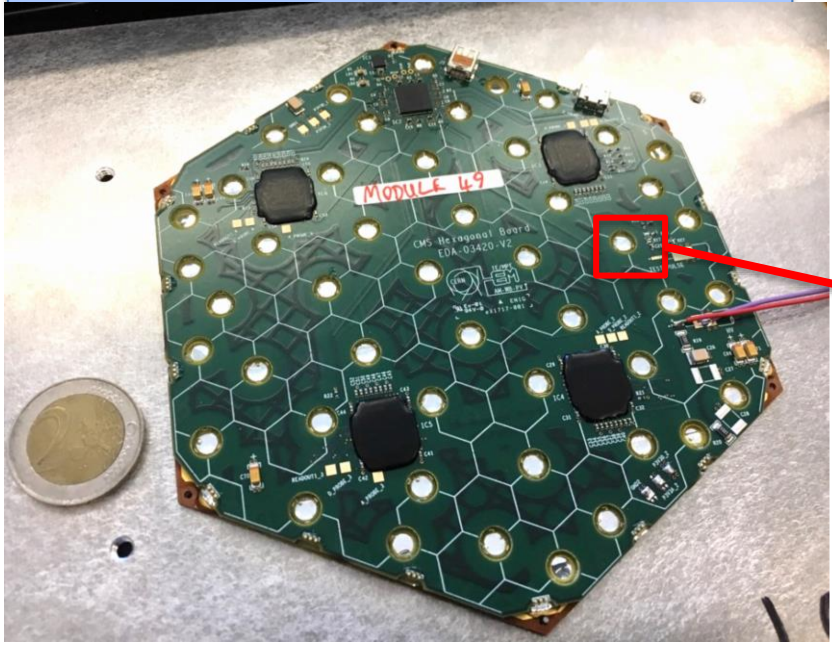
- Talk on Frontend System for HGCAL by Irfan

Module parts

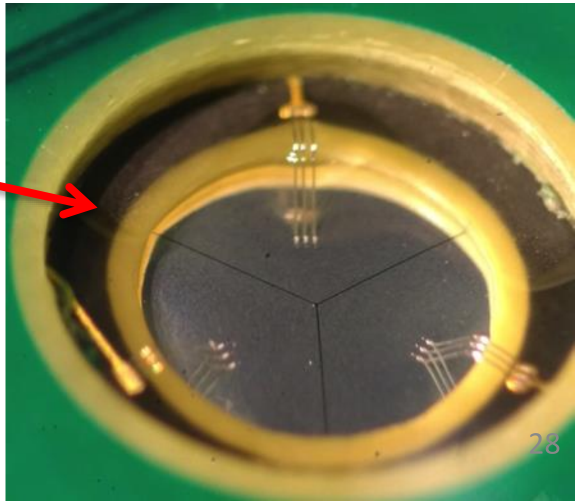


* Poster on baseplate development and its Measurements using CMM by Mukund

**Silicon sensor glued to baseplate and PCB containing front-end electronics**

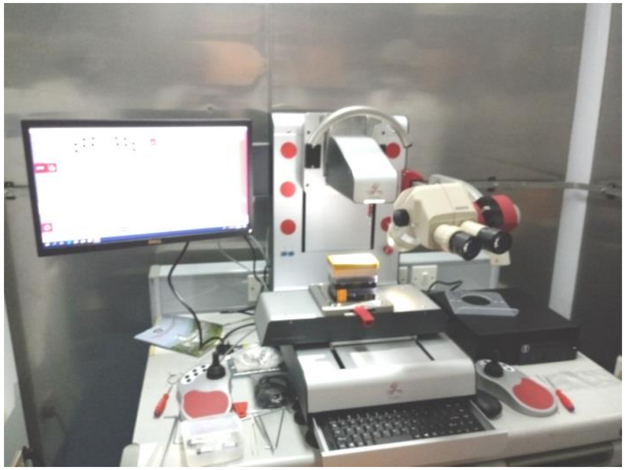


Wire bonding from PCB to silicon through holes

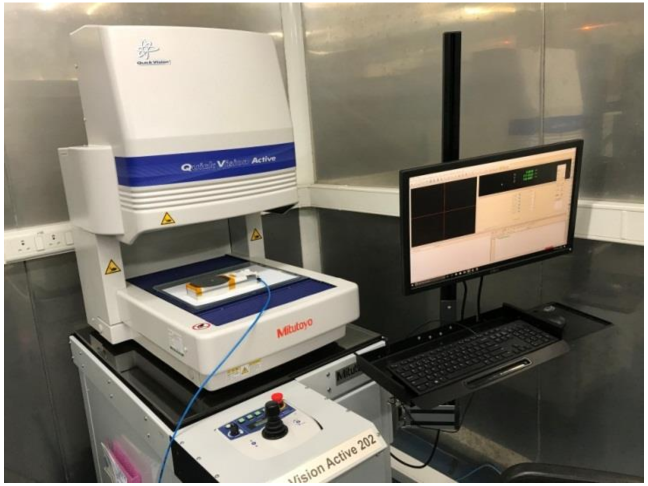


# Existing instruments in the lab

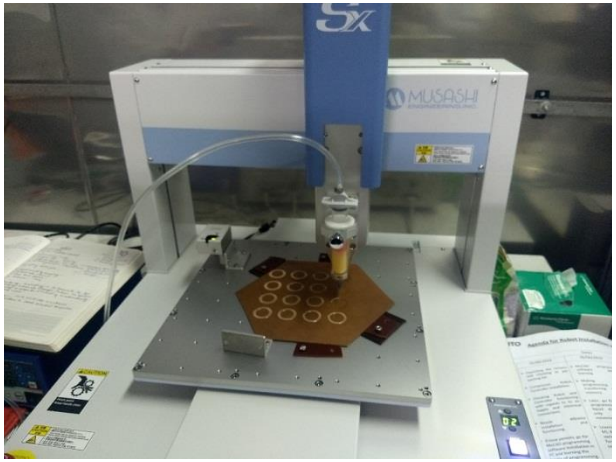
Wirebonder
Delvotec 6400 – used for Belle II SVD
Working area: 150 x 200, 25mm in Z
Suitable for up to 6” wafers



Wire Pull Tester
XYZTEC condor sigma lite



Coordinate Measuring Machine
Mitutoyo Vision Active 202
Working area: 250x200x150mm



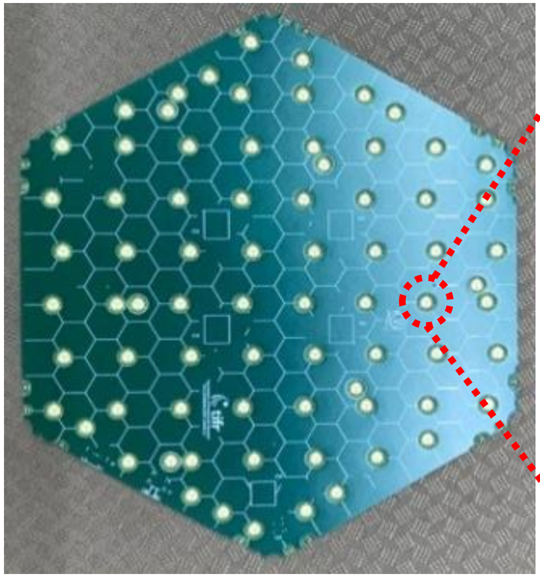
Mini Gantry
Mushashi SM-300SX-3A

- Leica M80 Microscope(90X)
- Motic Microscope (100X)
- Fisnar F7300N mini gantry
- Optical table (180x90cm)
- Additional 300 Sq ft of clean room area added

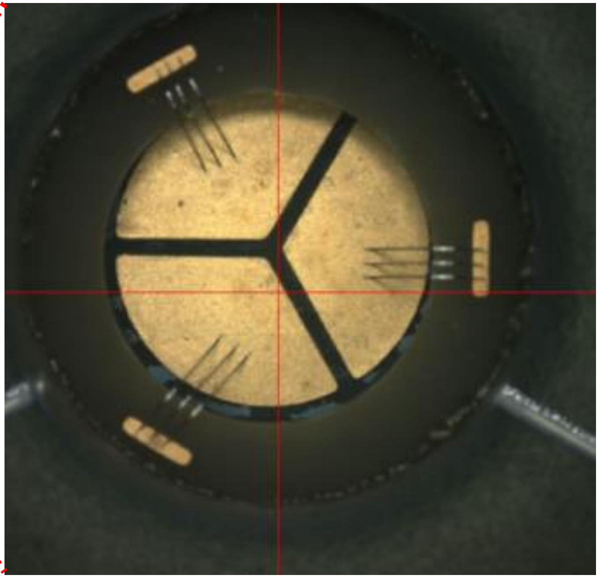
## On the way to get:

- Aerotech Main Gantry

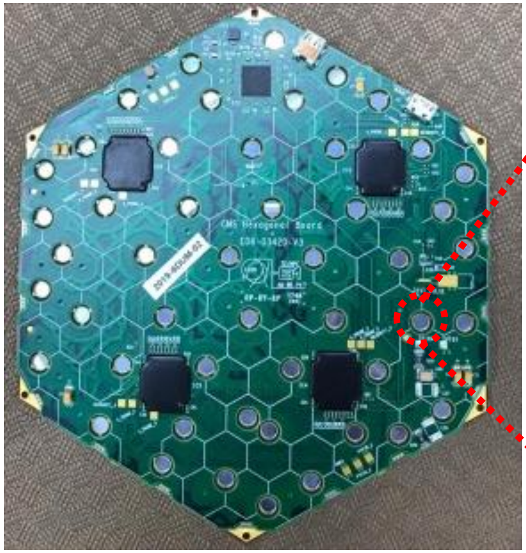
# Wirebonding studies



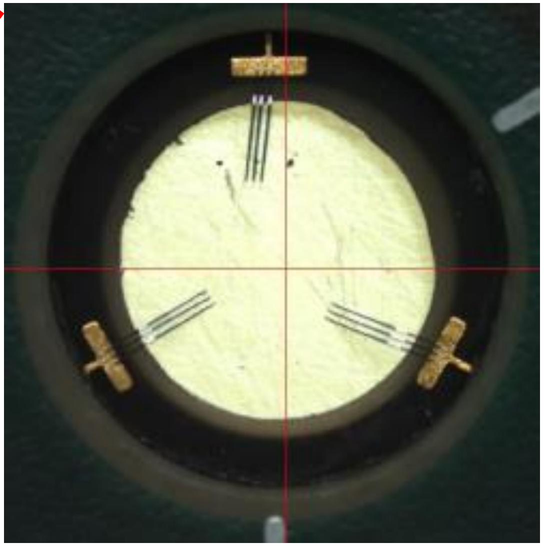
Dummy 8” HGCAL PCB



One of the stepped holes



6” HGCAL prototype module



One of the stepped holes

Small hole size : 4 mm
Big hole size : 6 mm
Step size of = 0.6 mm
Bonds at 120° locations

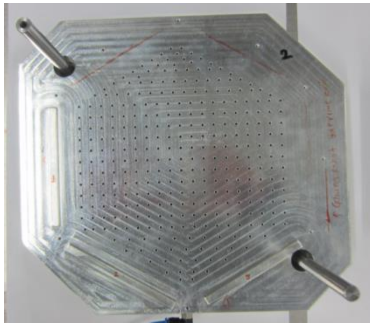
Automatic program has been developed for this application

Dummy 8” HGCAL PCB received from Micropack

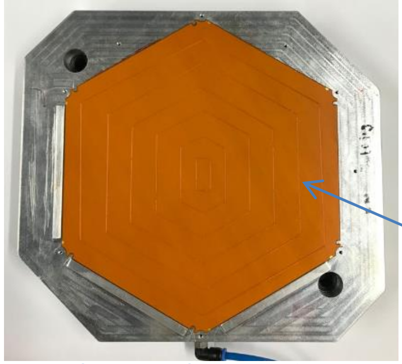
6” prototype module is from UC Santa Barbara

# Dummy HGCAL module assembly

**Designed and produced: 1) Multipurpose jig, 2) Sensor jig, and 3) PCB pickup jig**



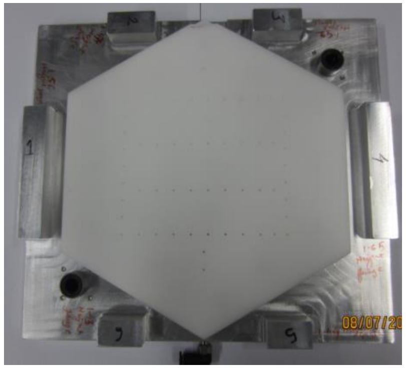
Multipurpose jig



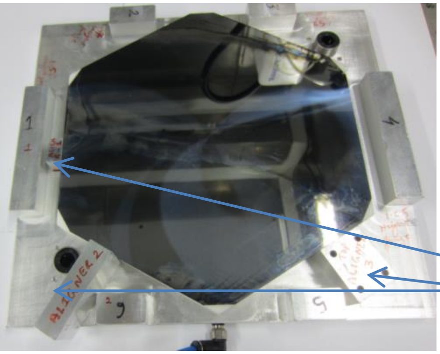
**Sensor alignment and placing setup**

glue pattern on baseplate

Baseplate aligned on multipurpose jig

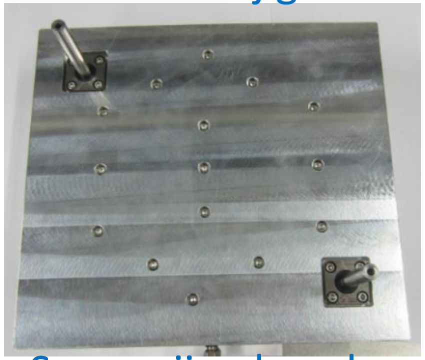


Sensor jig

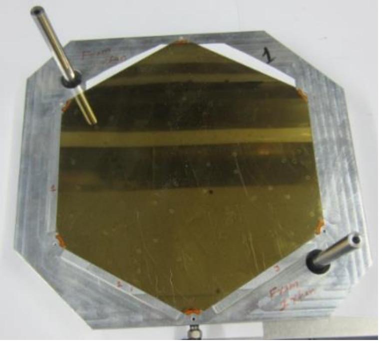


Aligners for sensor ( 8” )

Sensor aligned on jig



Sensor jig placed on multipurpose jig

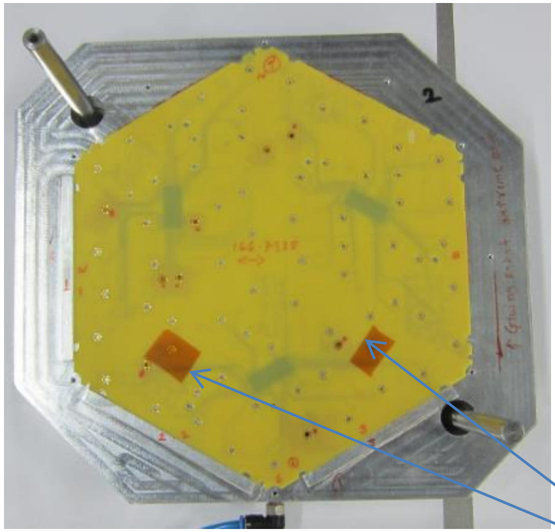


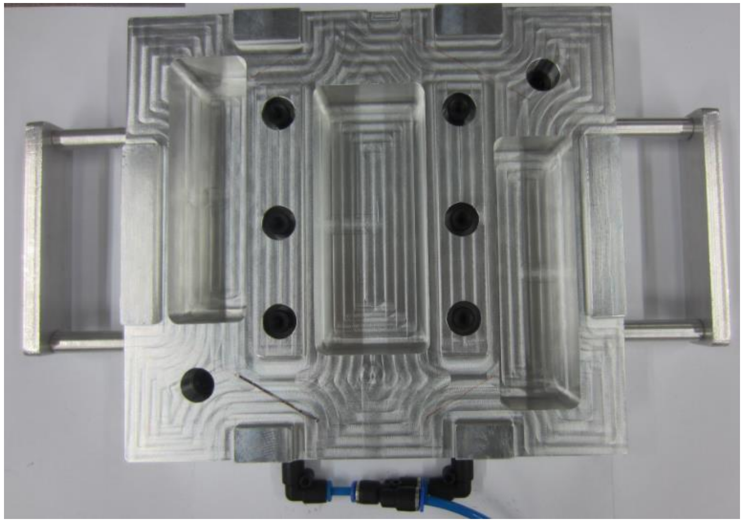
Sensor on baseplate

## After gluing the sensor:

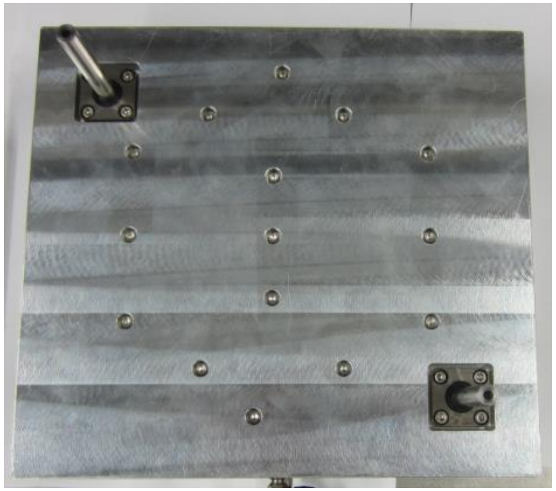
- Flatness of baseplate + sensor: 0.2658 mm
- Thickness of baseplate + sensor: 1.261 mm
- Glue thickness: 0.06 mm

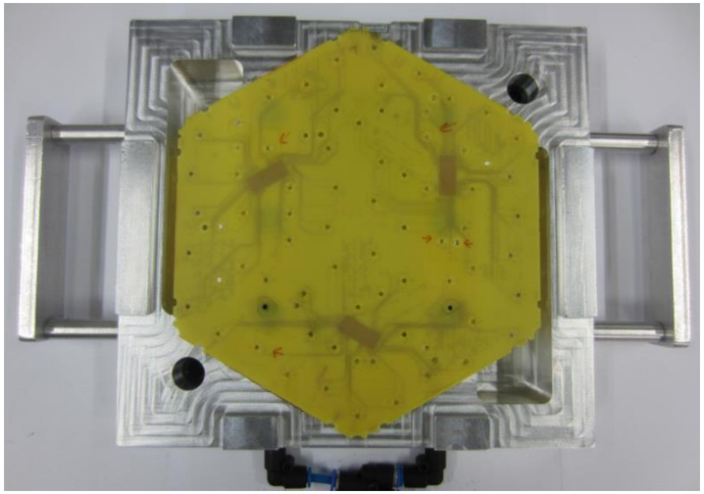
# PCB pickup setup


PCB aligned on multipurpose jig

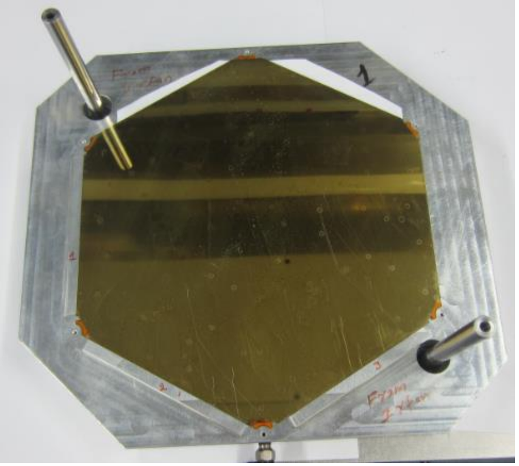

PCB pickup jig

Placed tape to avoid interference with vacuum cups

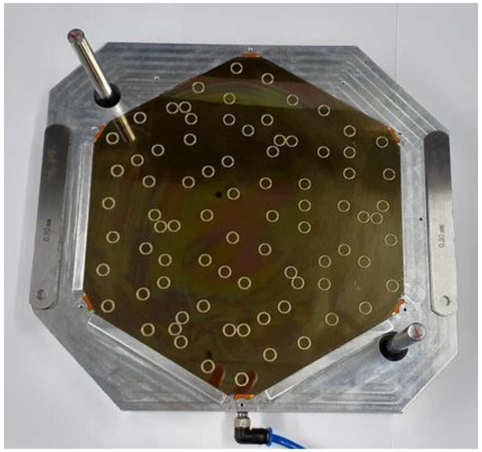

Placed PCB pickup jig
on multipurpose jig


PCB picked up

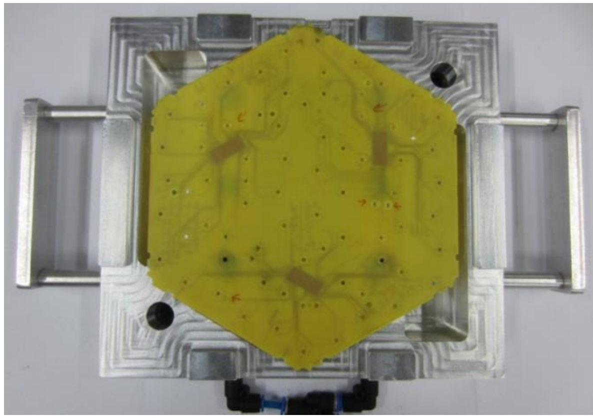
# Placing PCB on sensor



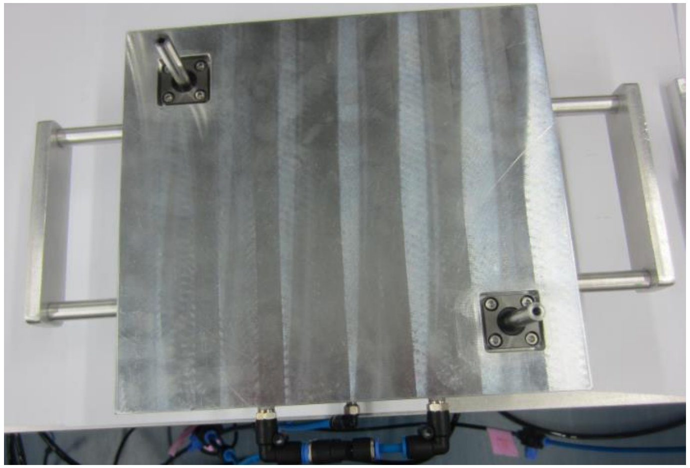
Baseplate and sensor on multipurpose jig



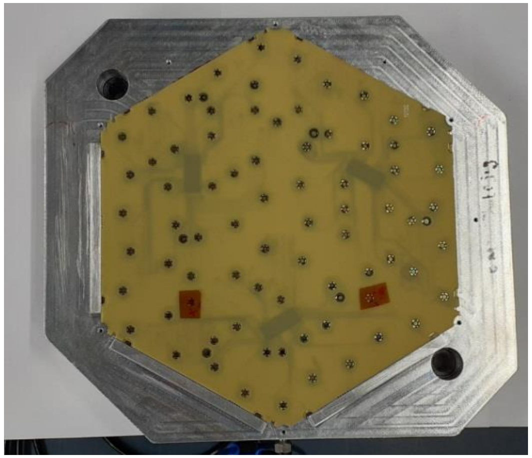
Glue – Araldite 2011



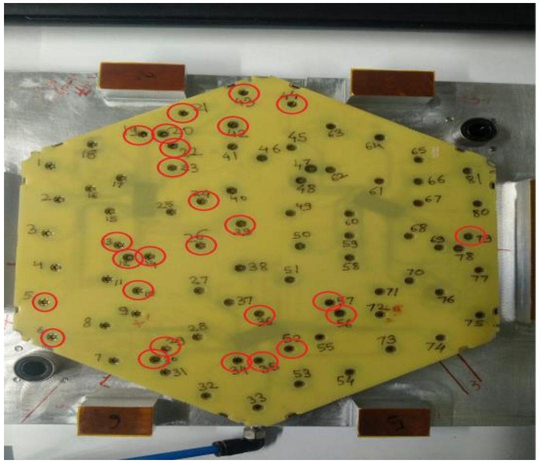
PCB pickup jig



Placed the PCB on multipurpose jig



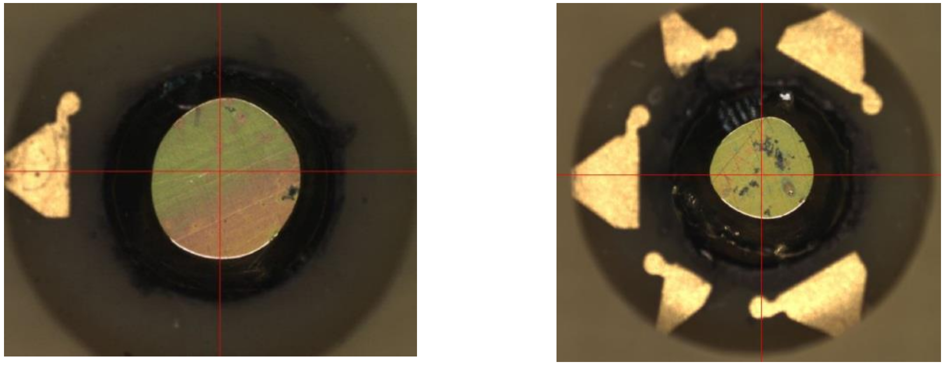
All together



Glue spread observed on above red circles

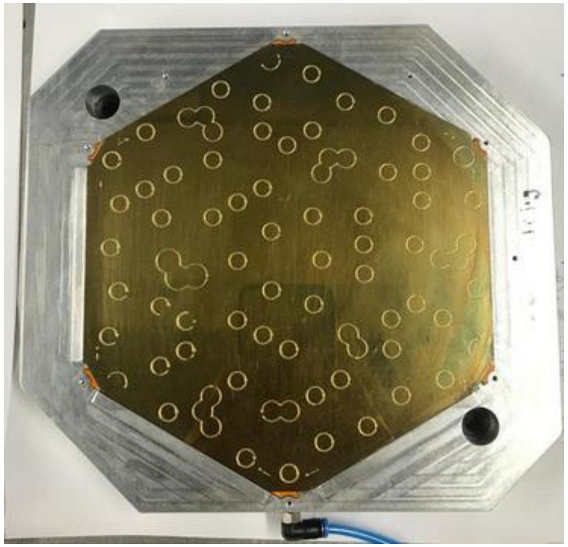
**Glue thickness achieved is around 50 microns between sensor and PCB**

# Optimized glue pattern, bonding, encapsulation

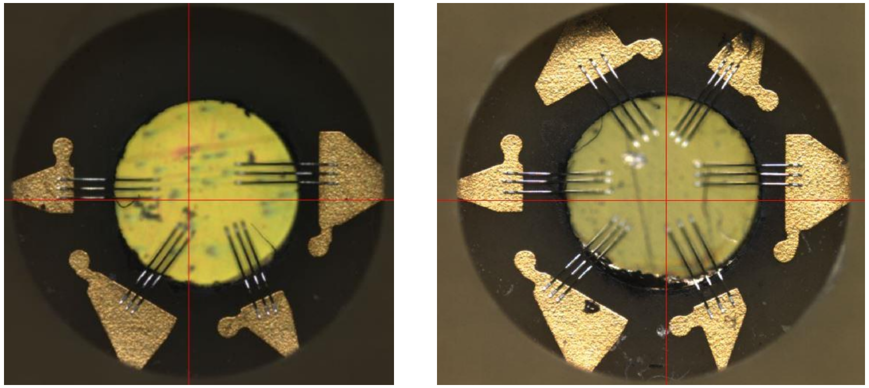


Glue spread seen on the sensor on some holes

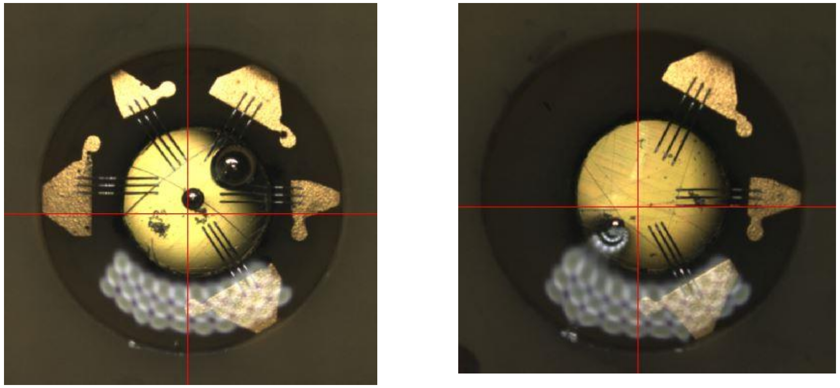
We are optimizing the parameters to avoid the glue spread in the next assembly



Improved version of glue pattern

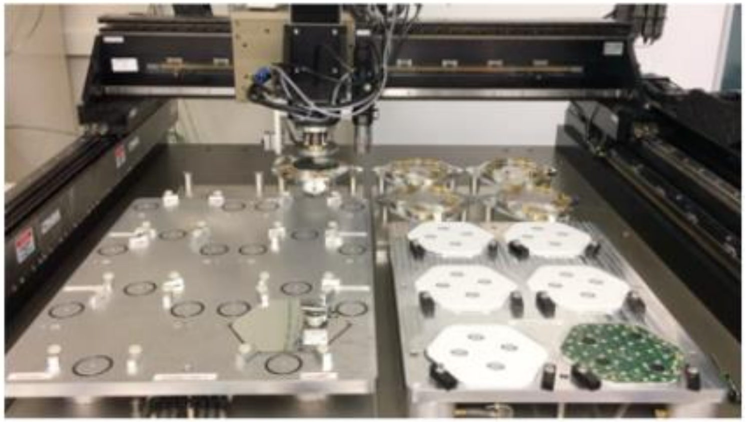


Wirebonding

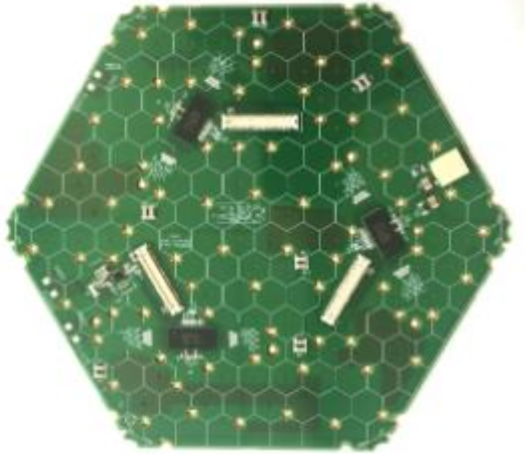


Encapsulation – Sylgard material

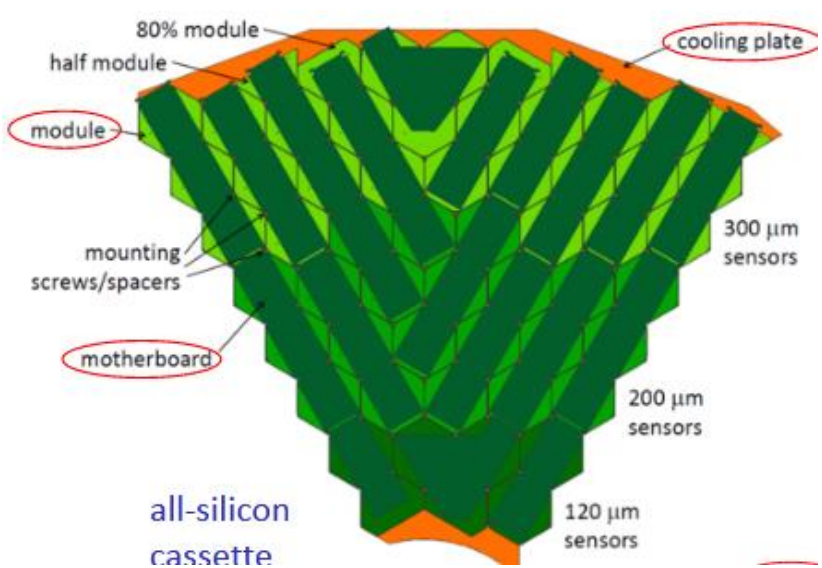
# Main Gantry and HGCAL modules in Cassette



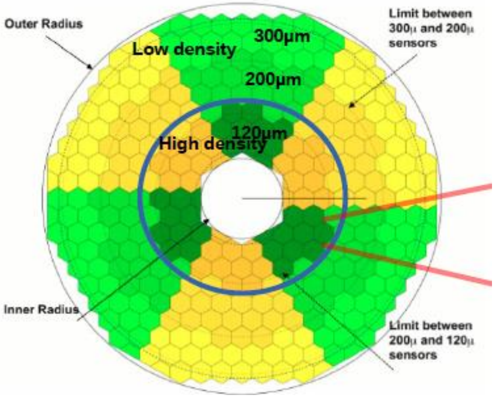
Procuring this main gantry
for mass production



An HGCAL module



HGCAL modules in Cassette



CE-E (Electromagnetic)
- 13 double sided layers

CE-H (Hadronic)
- 21 layers (full + mixed)

# Summary

Belle II SVD:

- For the first time, we are involved in such a high-precision detector project
- Starting from the scratch, we have come a long way – at par with the colleagues in Japan and EU
- All the assembly jigs are designed, produced and finetuned at TIFR
- Built up expertise on wire-bonding, gluing, pull testing, CMM analysis, and electrical tests
- Established/finetuned the assembly procedure, successfully built and installed the production-grade ladders to the Belle II detector

CMS HGCAL:

- Prototype developed
- Gluing, wirebonding, and encapsulation studies completed
- Need to develop jigs suitable for main Gantry – work in progress
- Waiting for the main Gantry to be delivered at TIFR ⇒ needed for the mass production of modules

Talk : Development of Muon Tomography for the validation of HGCAL by Pruthvi Suryadevara

Poster : Geometrical description of HGCAL in CMS software framework by Pruthvi Suryadevara

Thank you