# 3D Pixel Modules for the ATLAS ITk

Istituto Nazionale di Fisica Nucleare

# Introduction

**My activities here**

- ATLAS
  - assembly and testing **of modules for the upgrade of the Inner Tracker di ATLAS** (ITk)
  - SEU and readout tests for the ITkPix
  - reporting group → creating plots and dashboards for monitoring the production quality and advancement
- FCC/CEPC
  - development of **HV-CMOS pixel detectors for future e+e-** colliders
  - CREMA project

**Today's presentation**

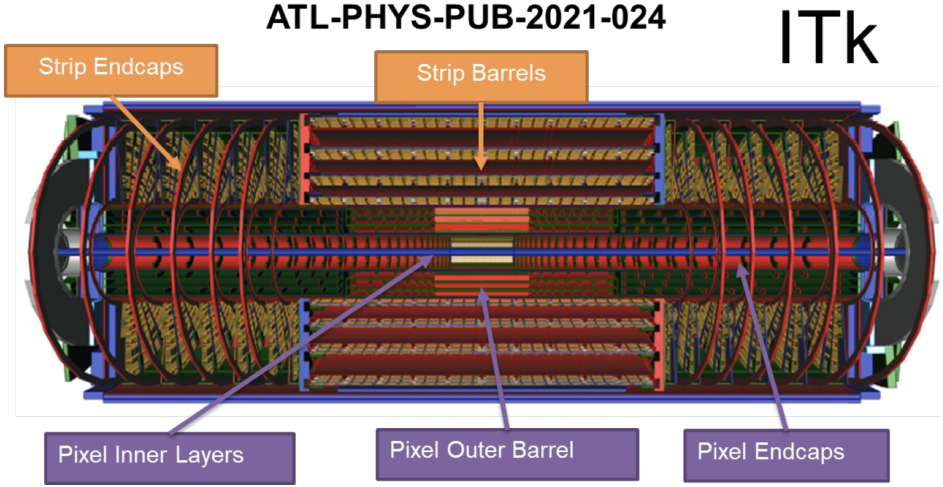
- **last 2/3 month progress on triplet modules**
- **last progress on ATLASPix3 modules**

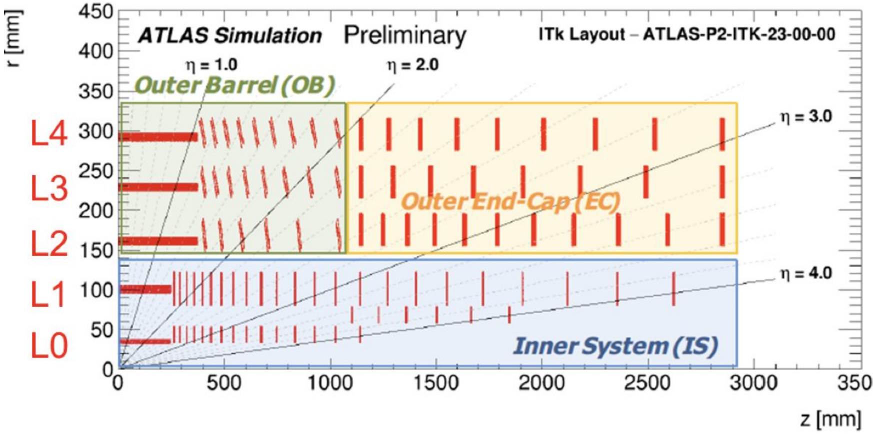
# ATLAS Inner Tracker - ITk

**HL-LHC** will reach a **luminosity of 5-7.5 $10^{34}$cm$^{-2}$s$^{-1}$**

- ATLAS Inner tracker will be replaced with a **new all silicon detector** (pixels and strips) the **ITk**

**ATL-PHYS-PUB-2021-024**



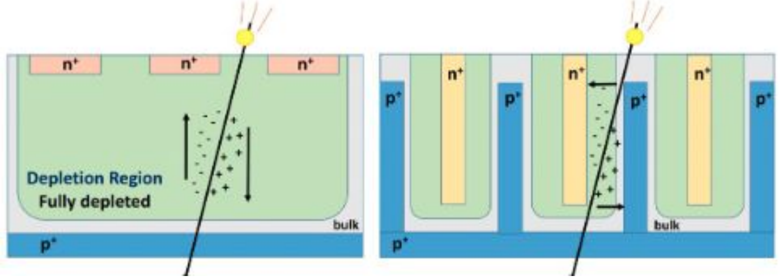


**ITk pixel layout** - 5 layers of pixels

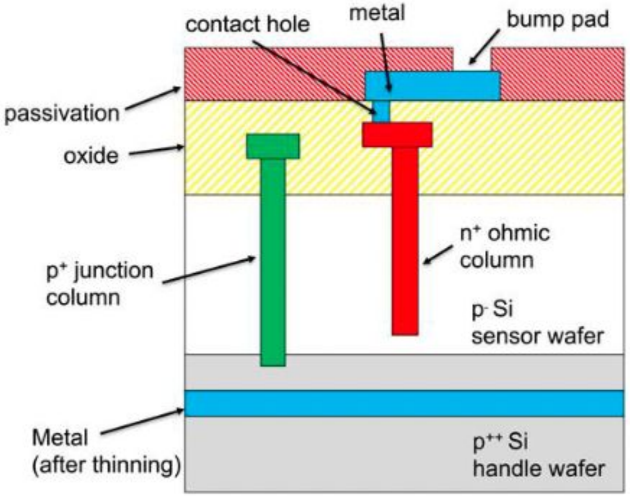
- L2-L3-L4 quad modules (planar, 150 μm)
- L1 quad modules (planar, 100 μm)
- **L0/L0.5 triplets (3D sensors)**

# 3D sensors

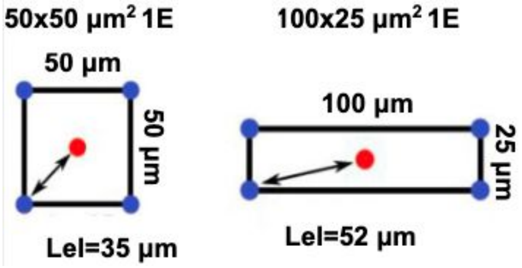
- **Planar sensors** -> standard pixel technology, n+ implants in p bulk surface
- **3D sensors** -> n+ and p+ columns vertically implanted in p bulk
    - used il L0/L0.5 thanks to their **radiation hardness**



**3D sensors layout**

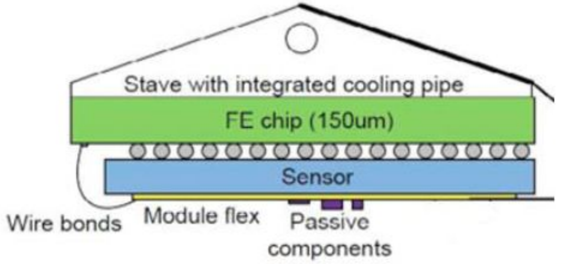


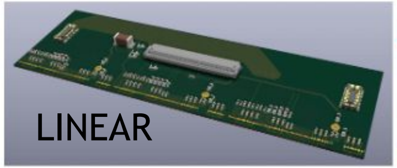
- **2 different 3D sensors layout**
    - 25x100μm
    - 50x50μm
- 3 different fabrication sites
    - FBK (Italy)
    - CNM (Spain)
    - SINTEF (Norway)
- 150μm active thickness with 250-270 μm total thickness

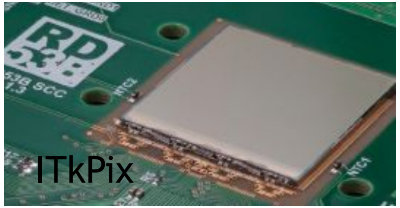


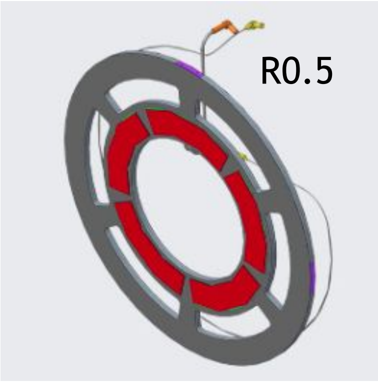
# ITk pixel triplet modules

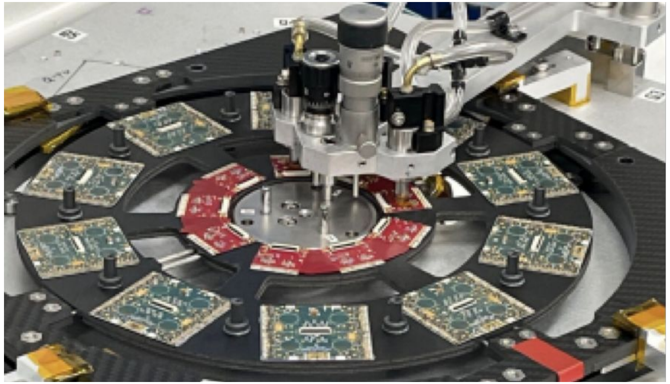
- A **triplet module** is composed by a set of **3 single bare modules attached in a flex**
- Only **3D sensors** (planar sensors used in quads)
- Two different triplets layouts
    - linear -> L0 barrel
    - **ring ->** R0/**R0.5 rings**
- Bare module -> 3D sensor + FE chip (**ITkPix**) connected by bump bonding
    - designed by RD53 collaboration
    - 65nm CMOS technology
    - 400x384 pixels (50x50µm$^2$)
- each module is then attached on a mechanical support
- **I work on test and assembly of 3D R0.5 triplets modules**











# Instrument description (1)

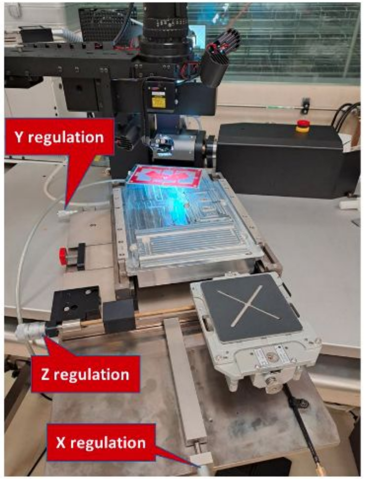
## Triplet Assembly Setup

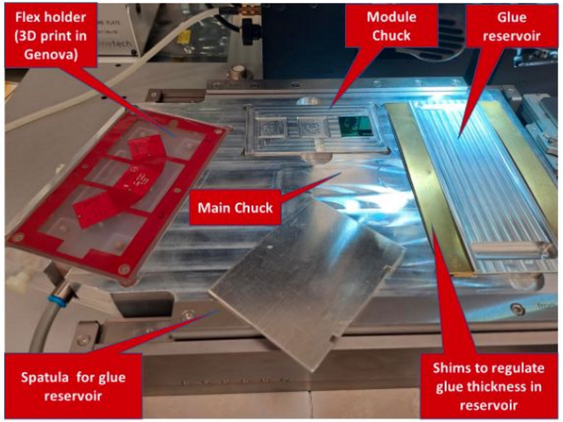
Dye bonder similar to IFAE: *Fineplace pico rs*

Micrometers:

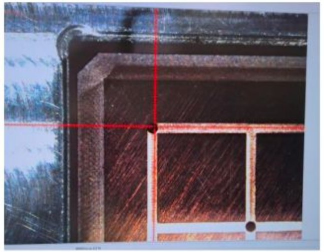
- 3 on the base for x, y, z regulation
- 1 on the pickup place arm for angular regulation

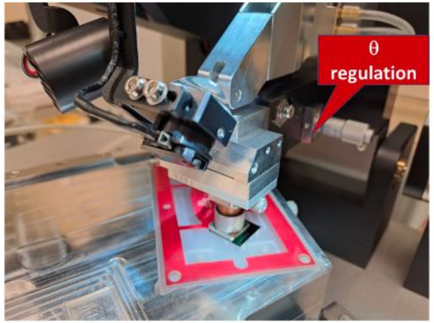
The pick-up tool is used not only to grab the modules, but also to apply the glue on the flex by clipping a stamp on it.





A prism projects on a camera both the ick-up tool and the assembly jig. The camera can be moved horizontally to check the alignment on the two corners of the wire bond line.





# Instrument description (2)

## Pickup tools

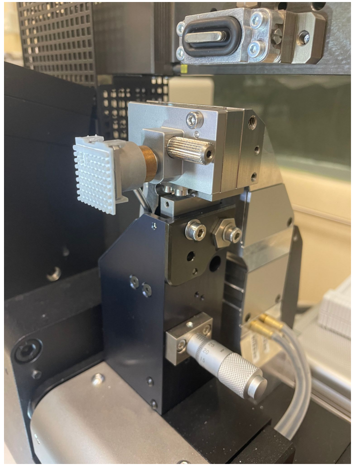
- older smaller **pickup tool**, showed before, used for **glue deposition**
- bigger **pickup tool**, used for module **put-down**

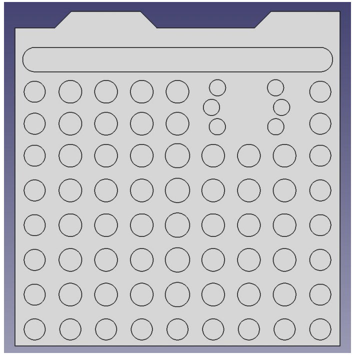
## Stamp

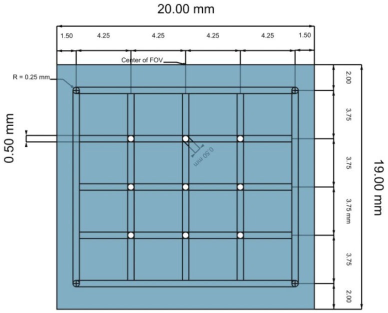
- 3D printed stamp
- **clipped** to **pickup tool**

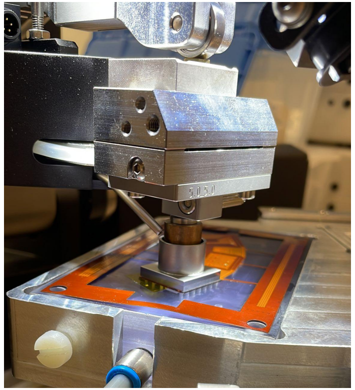
## Flex holder

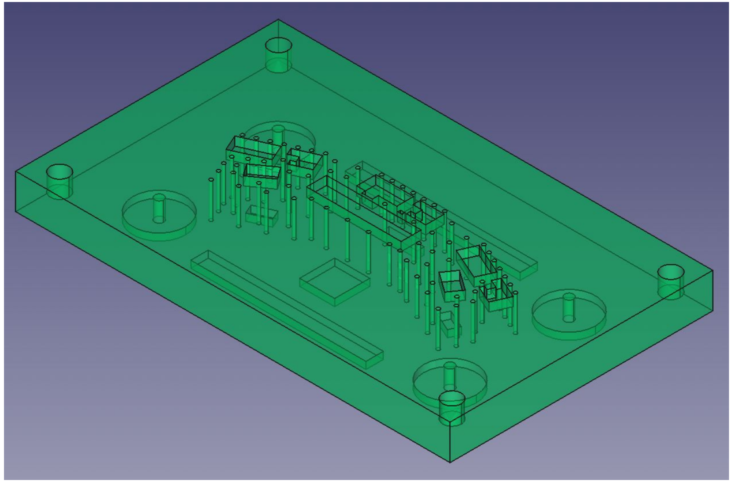
- 3D printed
- pieces of kapton to compensate for the **unevenness** of the **flex thickness**











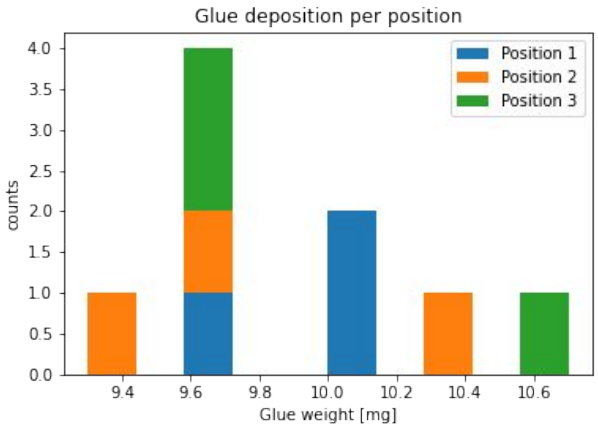
# Glue deposition

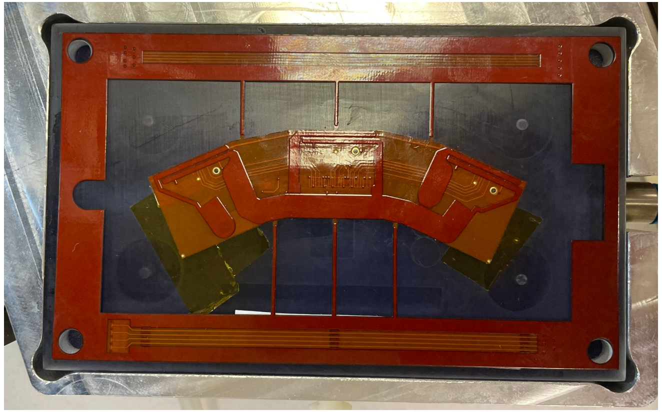
## Glue preparation procedure

- **Araldite 2011** is mixed using a standard nozzle, after each try a new nozzle is used
- glue is **deposited** inside the **pool**, right after it is expanded using the spatula and the **400µm** shims, and it is ready to be used

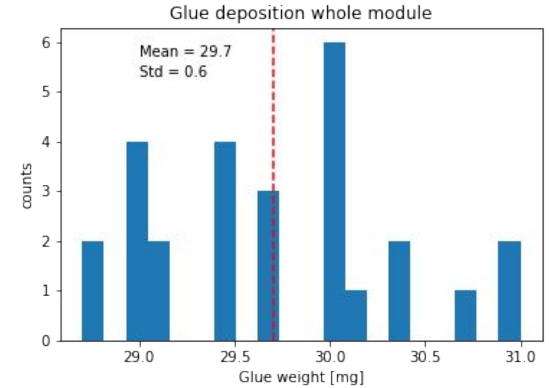
## Stamping method

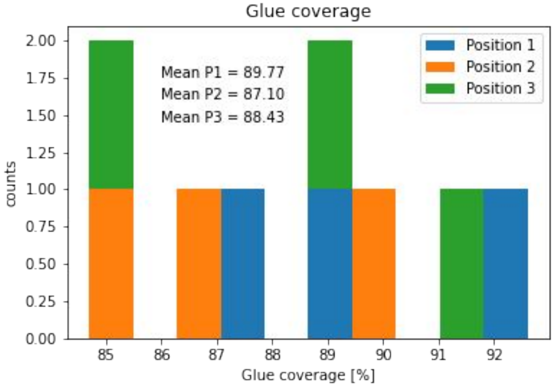
- **stamp** is clipped to old pickup tool and flex is kept with vacuum
- stamp is **soaked** in the glue pool using the **pick&place arm** with 0.75N force and arm is moved up as soon as force is reached
- same force and procedure is applied when the glue is **stamped** on the **flex**
- good **repeatability**





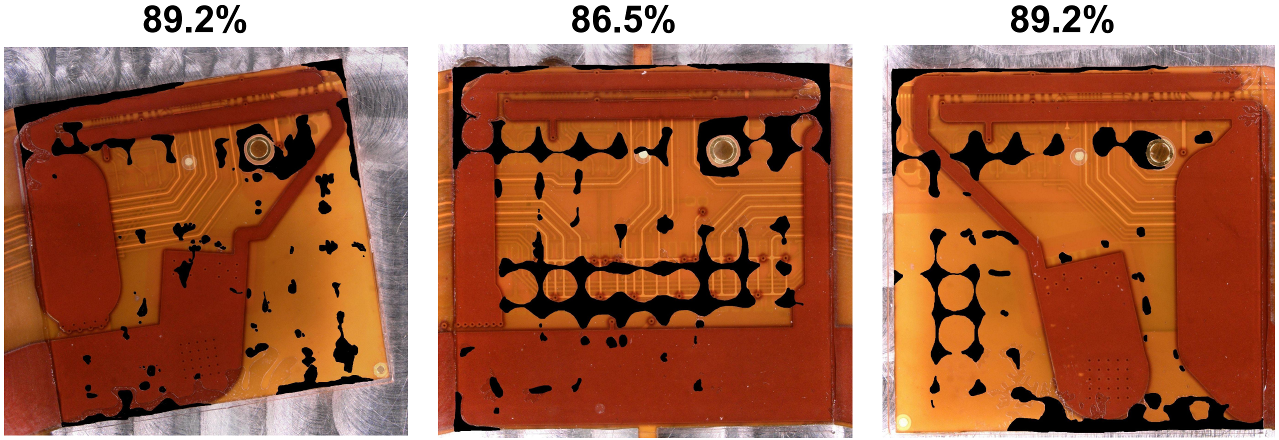
# Glue distribution



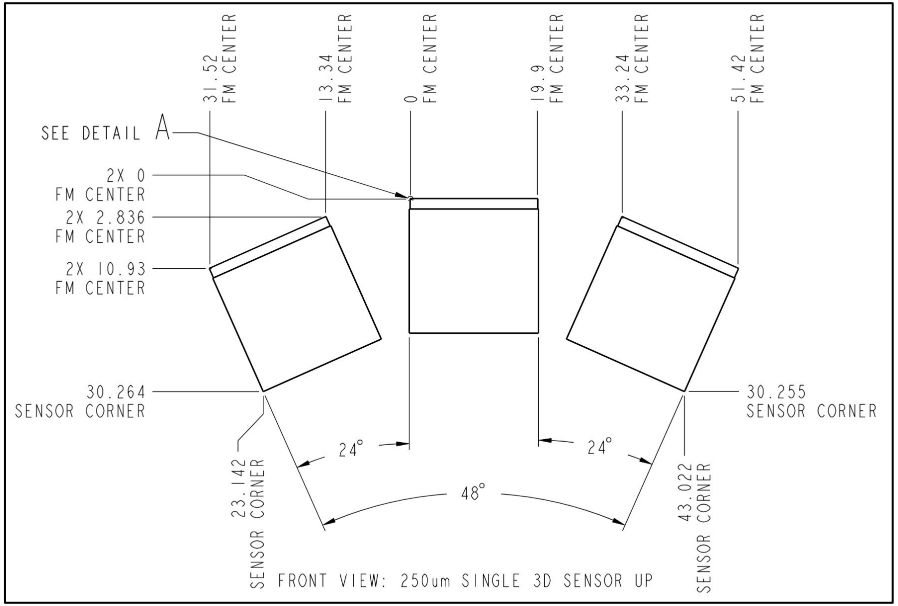


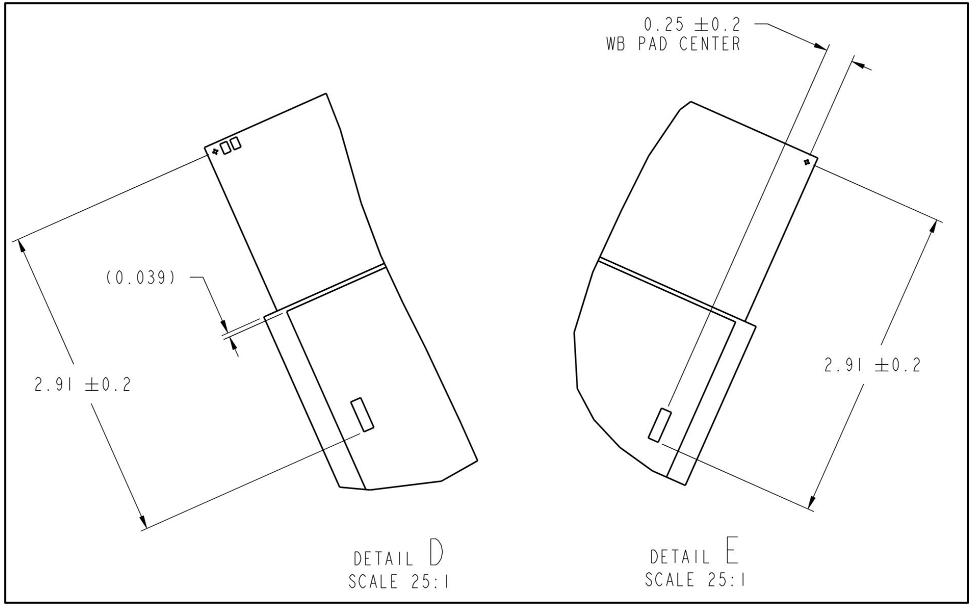
## Glue distribution

- **glue weight** distribution over all module is calculated combining all the weights for each position for each try
  - **within 1mg** for the all module → good repeatability of stamping method
- **glue coverage** distribution
  - evaluated with glasses
  - always **>80%** for every position



# Module drawings





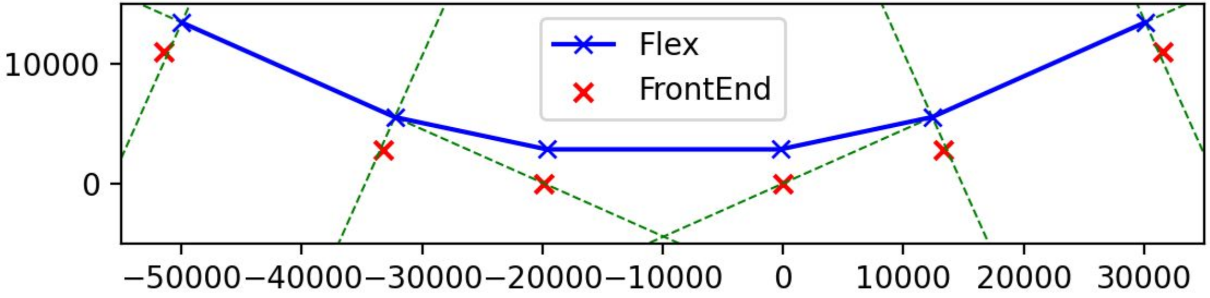
## Module

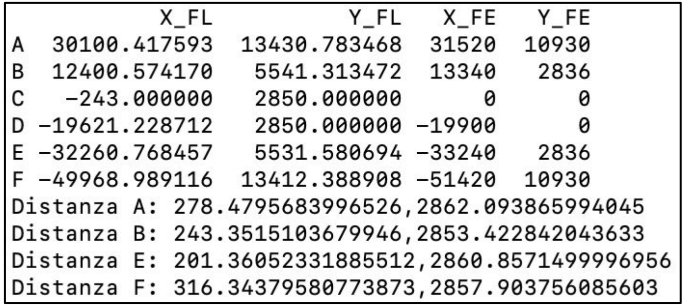
- **FE to FE alignment** (measured with fiducial mark on FE) → must stay within **50µm**
- **FE to Flex alignment** measured with fiducial mark on FE and outermost pads on the flex → very loose cut

# Module alignment (1)

## Module

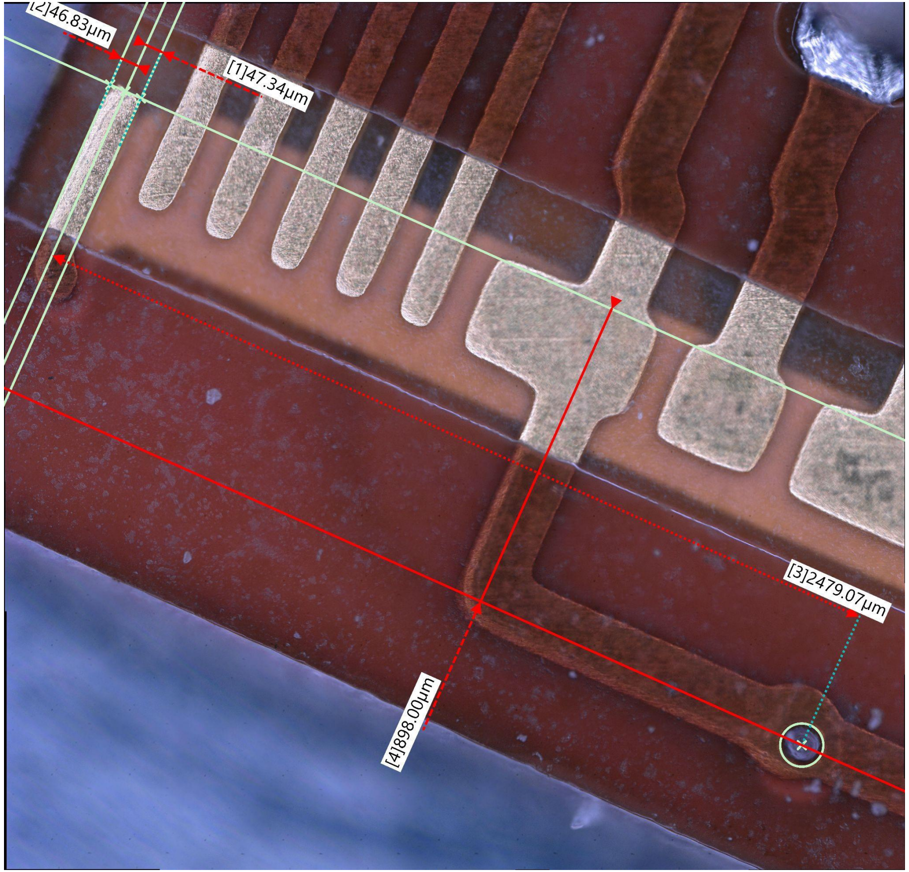
- **Pick&Place** machine only **allows** to **align FEs** wrt to **Flex** → using values from drawing it is **not sure** that I can **achieve** the **50µm tolerance** on the FEs relative position
- **procedure** for a **good** better **FE to FE alignment**
  - the **coordinates** of each of the **6 WB pads** of the **flex** are measured
  - the **FE** in the **center** is **aligned** considering the target value and assembled and **after assembly** its **alignment** with the center position of the flex is **measured**
  - considering the correct positions of the FEs, the measured positions of the WB pads and the relative position of the center **FE** to the **flex** the **relative position** of the two other FEs wrt the flex are **recalculated**
  - this method allows to stay within 50 µm





```
                X_FL          Y_FL   X_FE   Y_FE
A   30100.417593  13430.783468  31520  10930
B   12400.574170   5541.313472  13340   2836
C    -243.000000   2850.000000      0      0
D  -19621.228712   2850.000000 -19900      0
E  -32260.768457   5531.580694 -33240   2836
F  -49968.989116  13412.388908 -51420  10930
Distanza A: 278.4795683996526,2862.09386594045
Distanza B: 243.3515103679946,2853.42284204363
Distanza E: 201.36052331885512,2860.8571499996956
Distanza F: 316.34379580773873,2857.90375608560
```

# Module alignment (2)



**Flex Metrology**

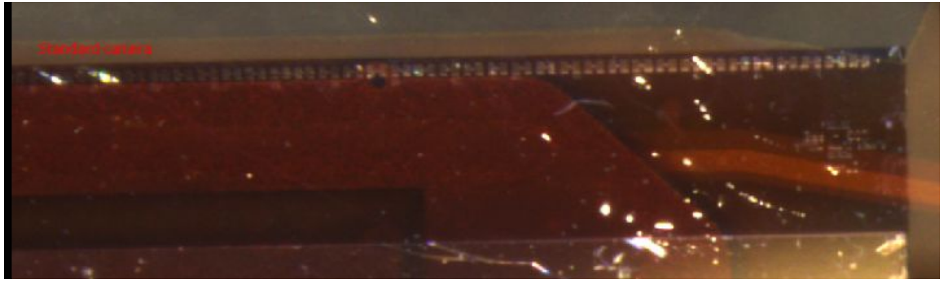
- alignment is measured with the pad of the flex and FE fiducial marker
- since the **pad** it is **not visible** on the **backside** → measure x and y **distance** with respect to one **via**, visible also on back side
  - distance between via and bottom of the pad
  - distance between via and center of the pad
- all **specifications are recalculated** after this measurement

# Module alignment (3)

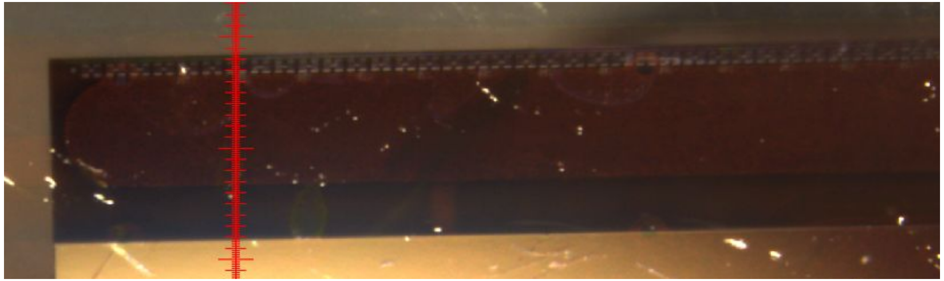
## Chip to Flex alignment

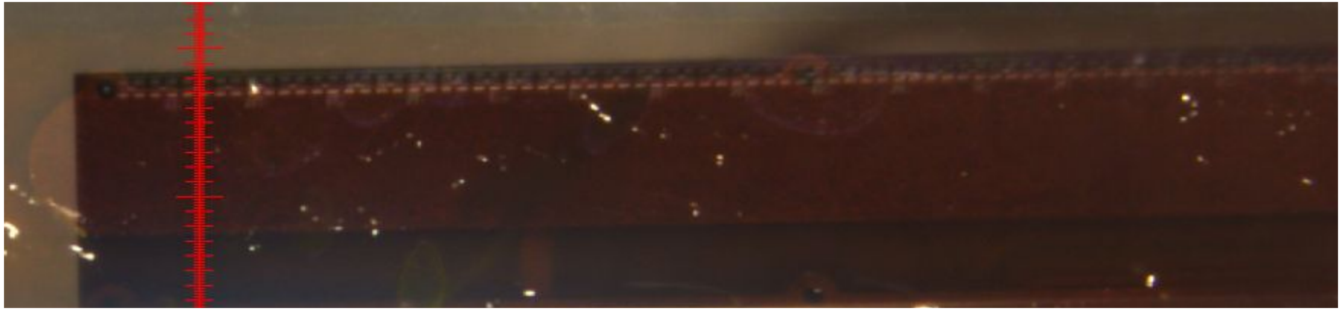
- alignment is made by **aligning** the **pads** to the **copper ground layer**
- then **FM cross** is moved in the **center** of the **via**

Right side alignment



Left side alignment



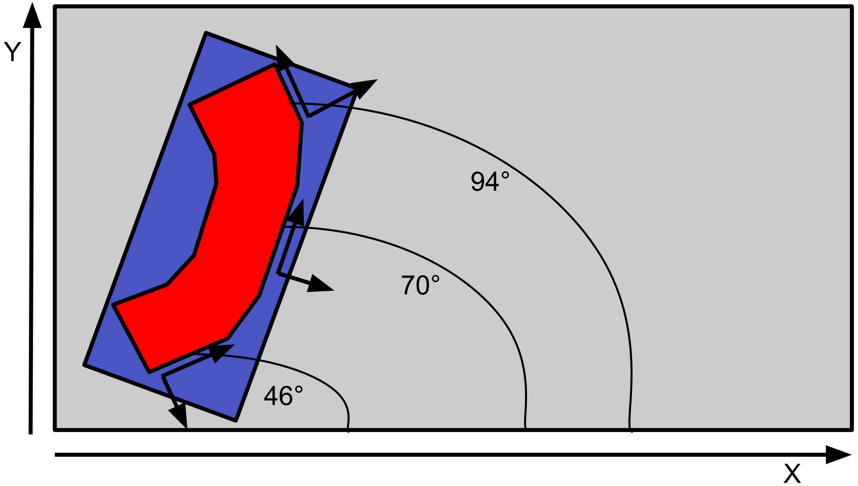


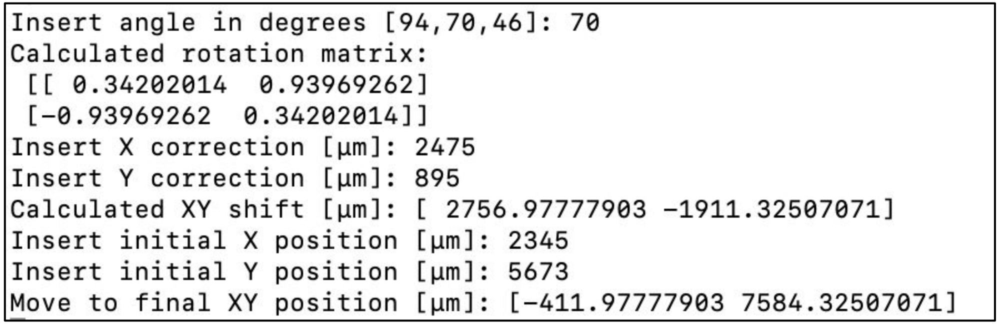
FM cross centered to the flex via

# Module alignment (4)

## Move chip to final position

- **chip** is finally moved to **final position** → used **distances calculated before**
- not simply move the micrometric screws of the quantity measured before → **flex** is **inclined** with respect to base → a movement in the system of reference of the base is different from the one wanted in the system of reference of the flex
- script to **calculate** the **rotation matrix** in each chip position and **transform** the **distances** in the system of reference of the flex in a **movement** of the **micrometric screws**





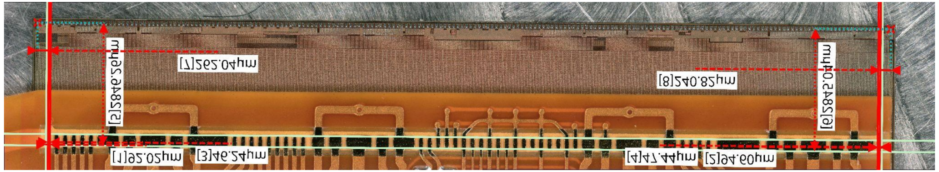
```
Insert angle in degrees [94,70,46]: 70
Calculated rotation matrix:
 [[ 0.34202014  0.93969262]
 [-0.93969262  0.34202014]]
Insert X correction [µm]: 2475
Insert Y correction [µm]: 895
Calculated XY shift [µm]: [ 2756.97777903 -1911.32507071]
Insert initial X position [µm]: 2345
Insert initial Y position [µm]: 5673
Move to final XY position [µm]: [-411.97777903 7584.32507071]
```

# Assembled modules - Alignment

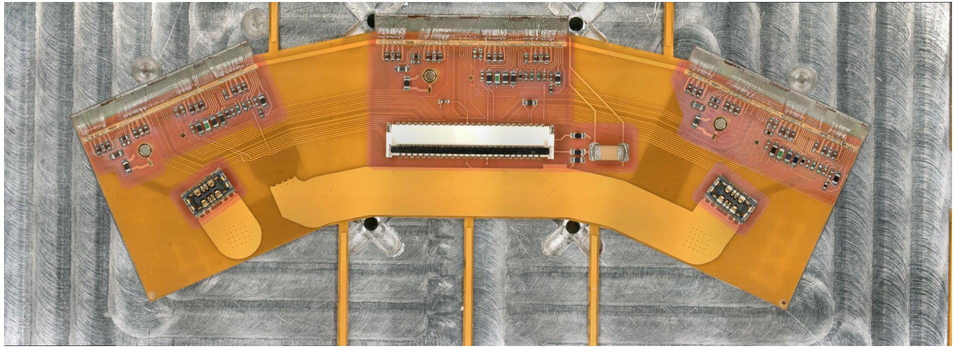
## Alignment results

- assembled **2 dummies** and **2 digitals** (one with ITkPixV2)
- example of results for the two digitals
    - FEs positions **within 50µm**
    - FE to Flex alignment within 200µm

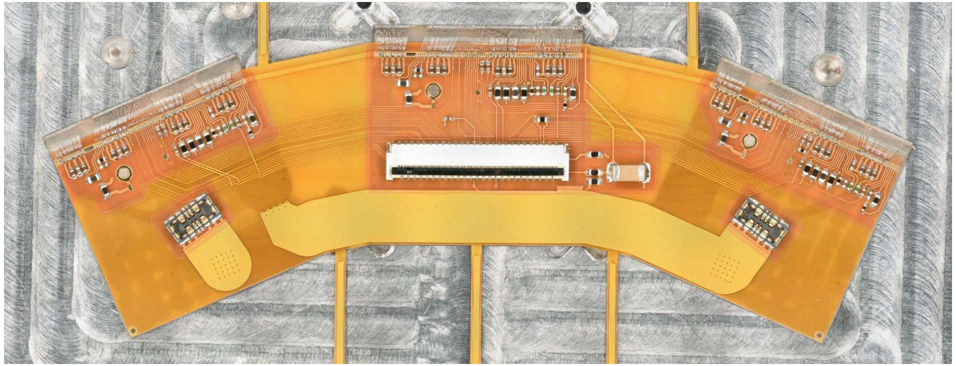
| FE to FE | DG1 | DG2 |
|---|---|---|
| $A\|_x$ | 17 | 38 |
| $A\|_y$ | 3 | 13 |
| $B\|_x$ | 15 | 25 |
| $B\|_y$ | 21 | 4 |
| $D\|_x$ | -6 | -8 |
| $E\|_x$ | -40 | 20 |
| $E\|_y$ | 37 | 34 |
| $F\|_x$ | -42 | 24 |
| $F\|_y$ | -18 | 10 |



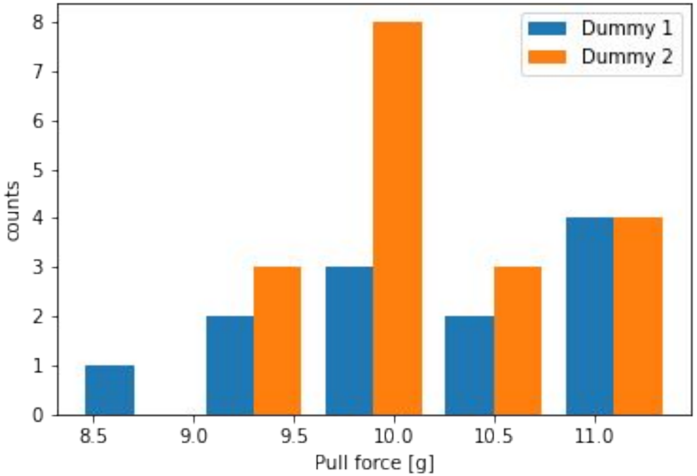
**20UPIR82302155 (DG1)**



**20UPIR82204114 (DG2)**

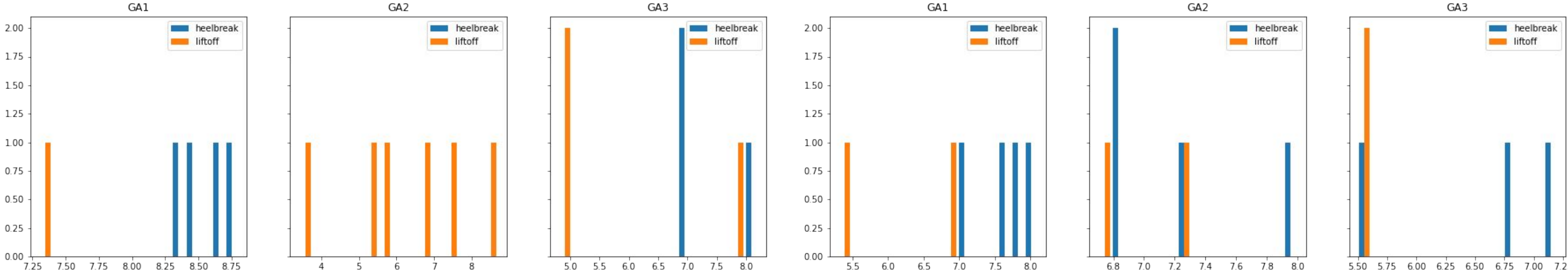


# Assembled modules - Wirebonding



**Wirebonding**

- good quality of flexes used for dummies
- quality of flexes of the batch used for digitals caused a lot of problems with wirebonding → low pull force mean, many liftoffs, some rebonding needed
- even with a more accurate cleaning results didn't improve as expected

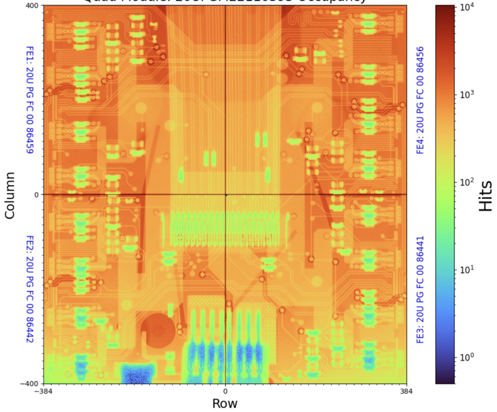


# Assembled modules - Testing

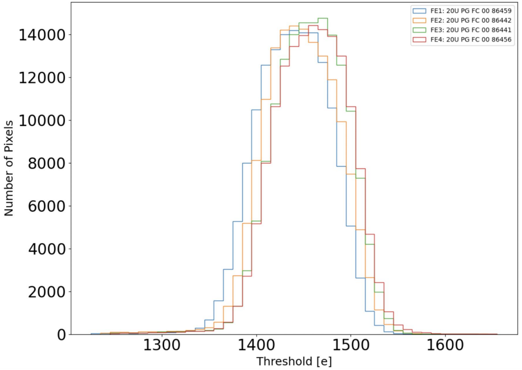
## Module electrical testing

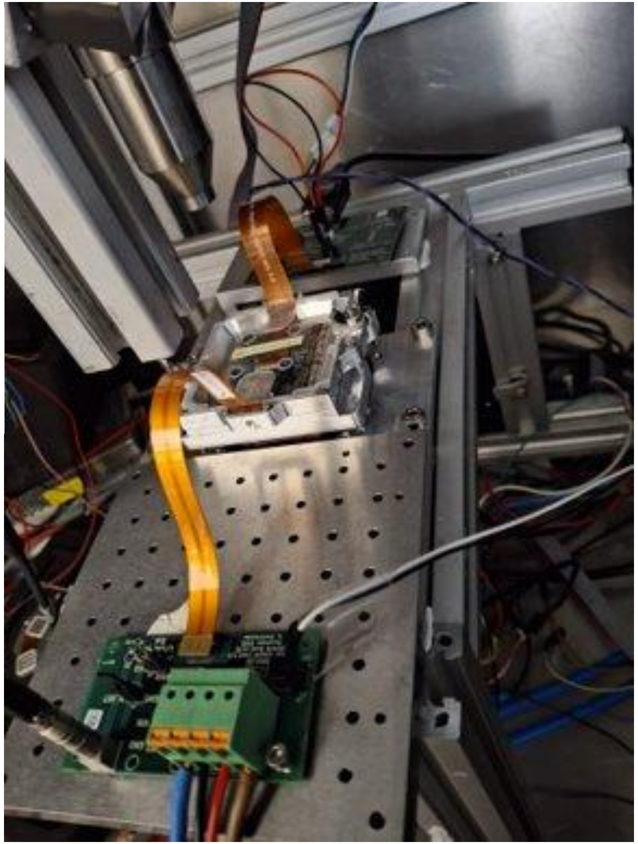
- after assembly modules are **tested** at **room temperature**
- measure **data-link quality**
- verify all **chip internal voltages and currents** and **SLDO regulators**
- measure **Injection capacitance** and **calibrate** internal **ADC** and calibration **voltage for chip tuning**
- verify **functionality** of **Low Power** operation mode
- check **minimal chip functionalities** with basic scans
- pixels **threshold tuning**
- ensure **good physics data efficiency** → check threshold **tuning** and **disconnected bumps** with dedicated scans and **X-Rays** scans

Quad Module: 20UPGM22110393 Occupancy



Module: 20UPGM22110393 ThresholdDist-0

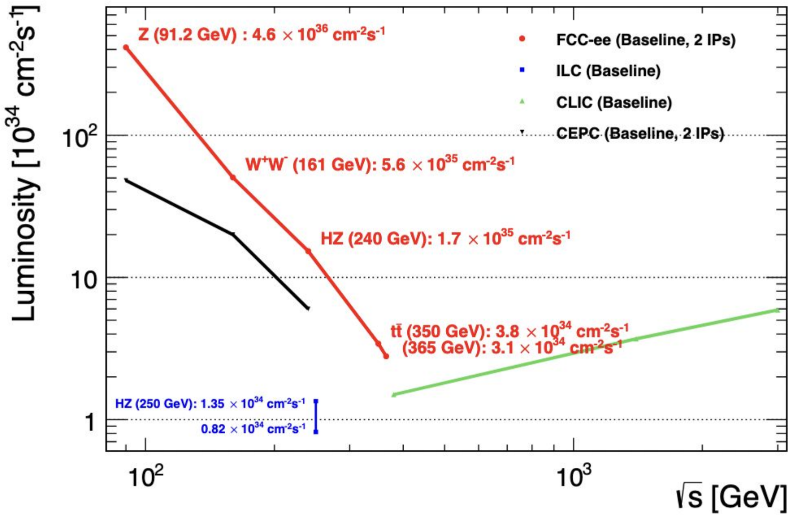


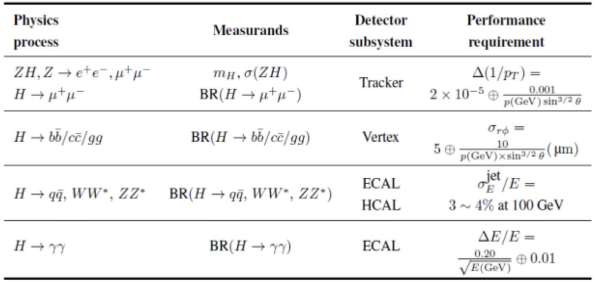


# Future $e^+e^-$ circular colliders

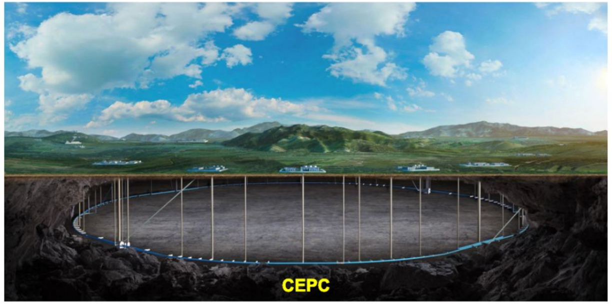
## FCC and CEPC

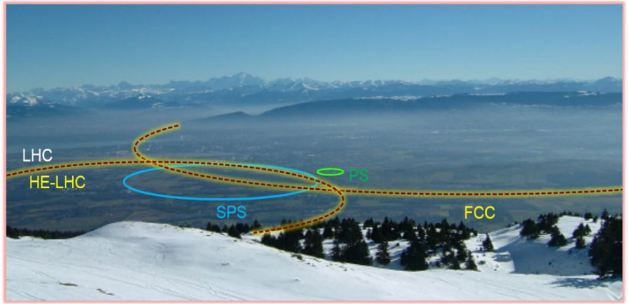
- proposed **future circular $e^+e^-$ colliders**
- **100km** double ring
  - **CEPC** → China
  - **FCC-ee** → CERN
- **energy** up to **tt threshold**
- luminosity up to **$4.6\text{x}10^{36}$ $\text{cm}^{-2}\text{s}^{-1}$** at the **Z pole**
- **high precision physics** at **electroweak** and **Higgs** sectors to unveil **small deviations** from **Standard Model** → **strict requirements** for detector **performance**
- different detector **concepts**, like **IDEA**



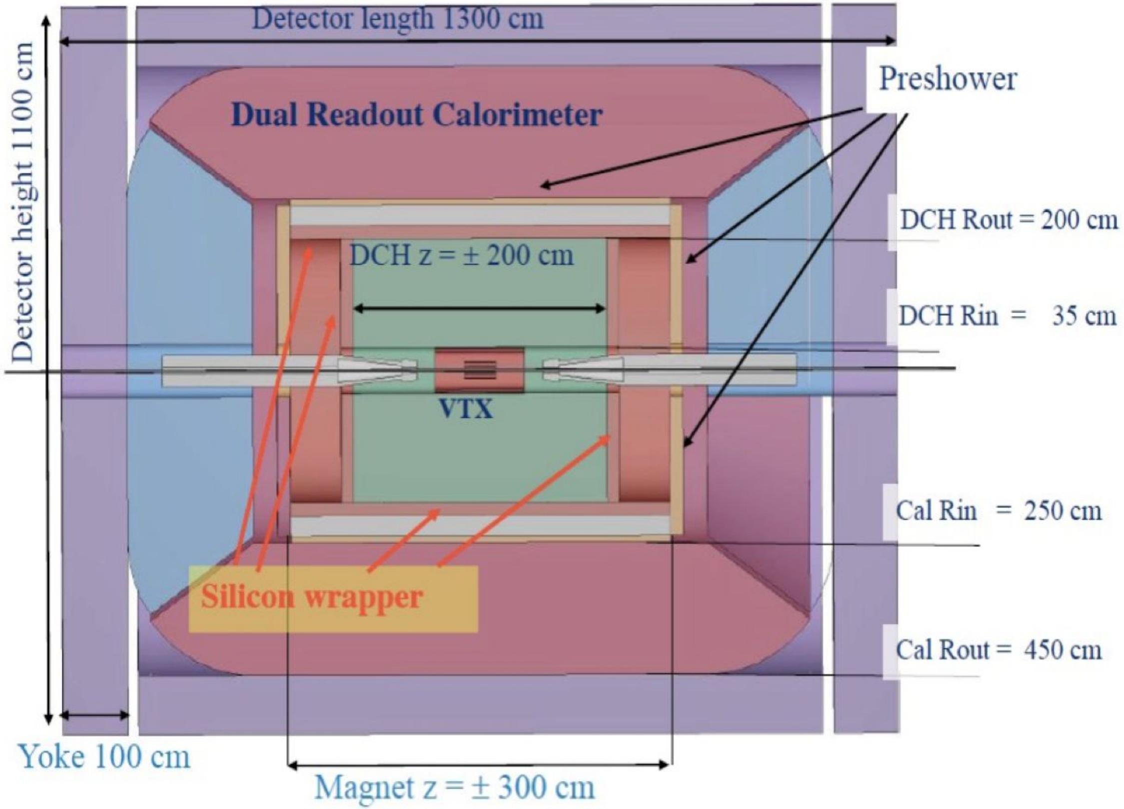


| Physics process | Measurands | Detector subsystem | Performance requirement |
|---|---|---|---|
| $ZH, Z \rightarrow e^+e^-, \mu^+\mu^-$<br>$H \rightarrow \mu^+\mu^-$ | $m_H, \sigma(ZH)$<br>$\text{BR}(H \rightarrow \mu^+\mu^-)$ | Tracker | $\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\text{GeV}) \sin^{3/2}\theta}$ |
| $H \rightarrow b\bar{b}/c\bar{c}/gg$ | $\text{BR}(H \rightarrow b\bar{b}/c\bar{c}/gg)$ | Vertex | $\sigma_{r\phi} = 5 \oplus \frac{10}{p(\text{GeV}) \times \sin^{3/2}\theta} (\mu\text{m})$ |
| $H \rightarrow q\bar{q}, WW^*, ZZ^*$ | $\text{BR}(H \rightarrow q\bar{q}, WW^*, ZZ^*)$ | ECAL<br>HCAL | $\sigma_E^{\text{jet}}/E = 3 \sim 4\%$ at 100 GeV |
| $H \rightarrow \gamma\gamma$ | $\text{BR}(H \rightarrow \gamma\gamma)$ | ECAL | $\Delta E/E = \frac{0.20}{\sqrt{E(\text{GeV})}} \oplus 0.01$ |





# The IDEA detector



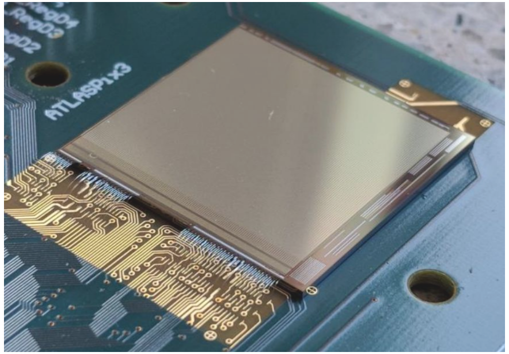
## IDEA concept detector

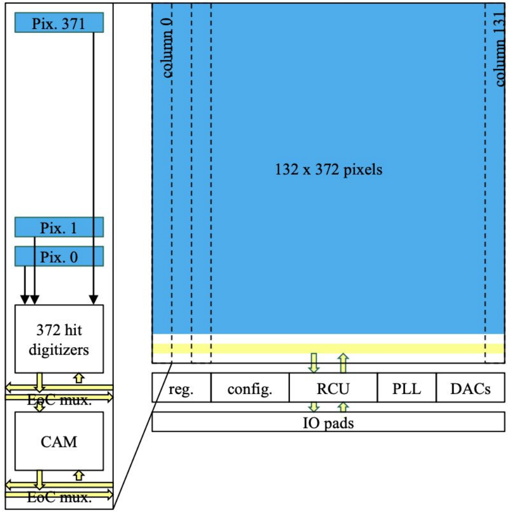
- Central light **Drift Chamber**
- **Silicon detectors** for precision measurements
  - **vertex region**
  - **silicon wrapper**
  - **DMAPS** (Depleted Monolithic Active Pixel Sensors) are a **suitable technology** for the outer layer of the vertex detector and the silicon wrapper → **ATLASPix3**
- Thin **solenoid** with 2T field
- Dual readout **calorimeter**
- **Muon** chambers

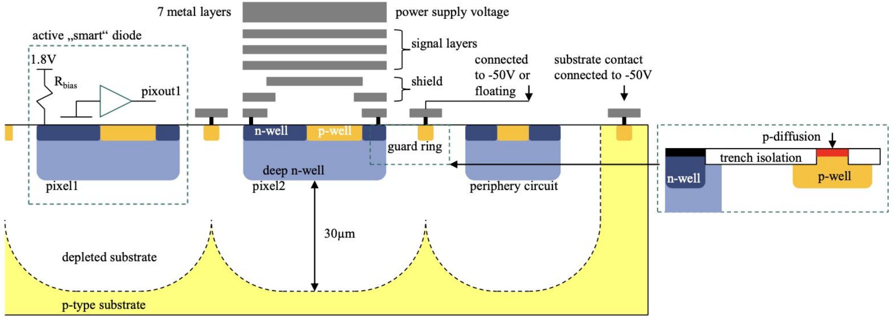
# ATLASPix3

## ATLASPix3

- Depleted Monolithic Active Pixel Sensor (**DMAPS**)
- **HVCMOS** technology
- full-reticle size **20×21 mm$^2$**
- **TSI 180 nm** process on 200 Ωcm substrate
- 132 columns of 372 pixels
- pixel size **50×150 μm$^2$**
- **breakdown** voltage ～**-60 V**
- up to **1.28 Gbps** downlink
- **25 ns timestamping** and **ToT** measurement
- **triggered** and **untrigger readout** are possible
- **SLDO regulators** for **serial powering**
- readout with **GECCO** readout Firmware/Software



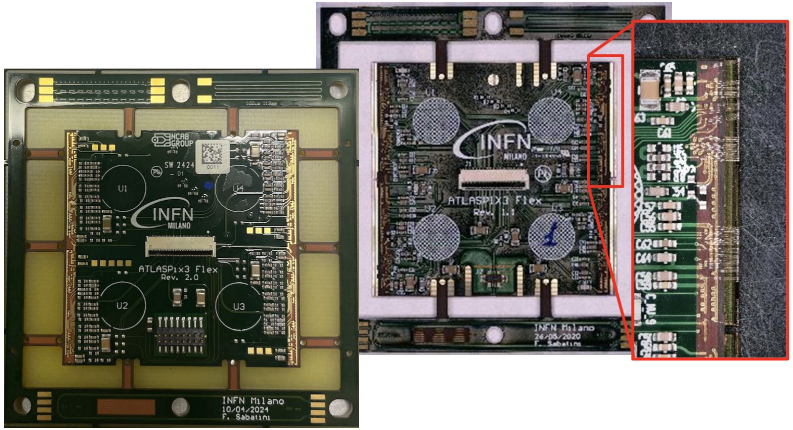


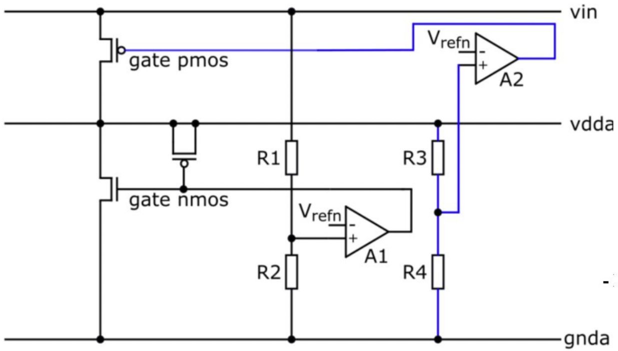


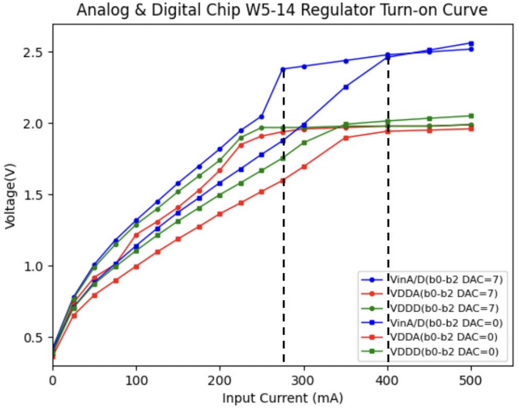
# ATLASPix3 - Serial Powering

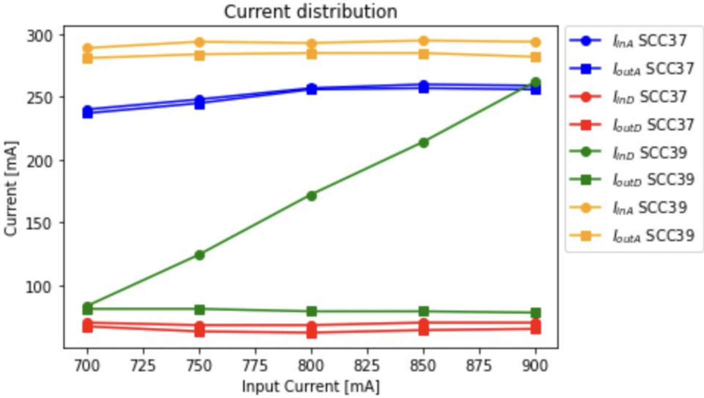
## Quad modules and serial powering

- we have developed **ATLASPix3 quad modules**, based on the ITk modules example, and **developed firm/software**
- **new** version of **flex** PCB implements **serial powering**
    - **characterization** of **SLDO** regulators
    - **operation** of **single chip** in serial powering mode
    - **emulate** connection inside the **modules** with single chips to study current/voltage distribution
- **next** step → build **serially powered chain** of modules





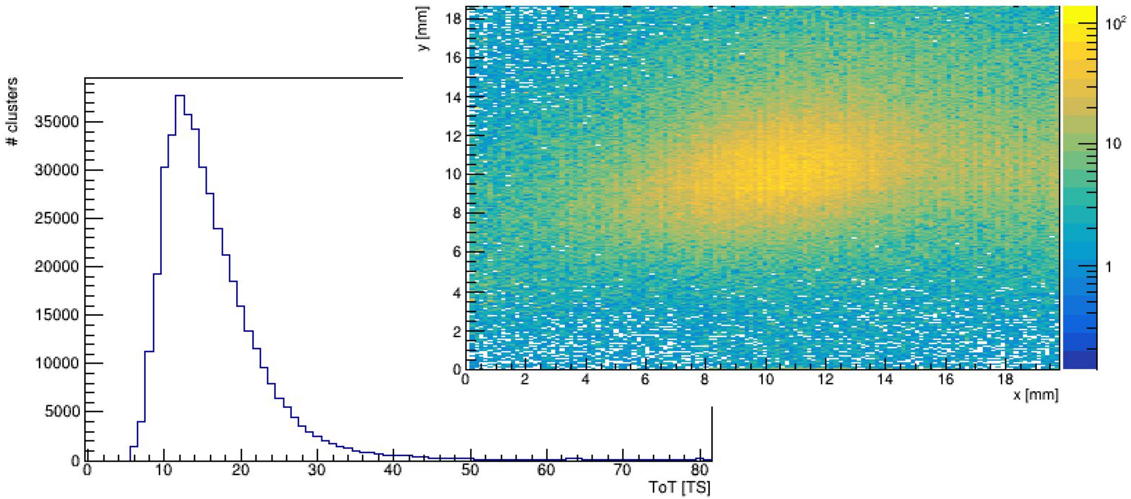




# CREMA project

## CREMA project

- aims to **study bending** of **low energy particles** in **silicon crystals**
- tests done at **CNAO** with **400 MeV/u C-ions** beam
- **signal doesn’t saturate** despite the high charge released in the sensor
- **sensible** to **small deviations** and **low bending efficiency**



# GRAZIE DELL’ATTENZIONE