Activities and developments on silicon sensors in Perugia

Livio Fanò*

*on behalf of all in Perugia involved in the presented activities
all the activities are supported by **University**, **INFN, MUR** and **EU**

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Different research areas:

Phsyics@Accelerator (high fluence, high rate and precision)

Space

Nuclear Physics/Dosimetry

Several R&D, qualification and construction activities ongoing in Perugia, some selected:

Silicon strip (CMS Phase2, FOOT experiment, HERD, AMS upgrade…)

LGAD

Pixel (a-Si:H)

SiPM

More specifically, activities are related to:

Design/development/assembly

Simulation

Mechanics/Cooling

Electrical and Mechanical Characterisation

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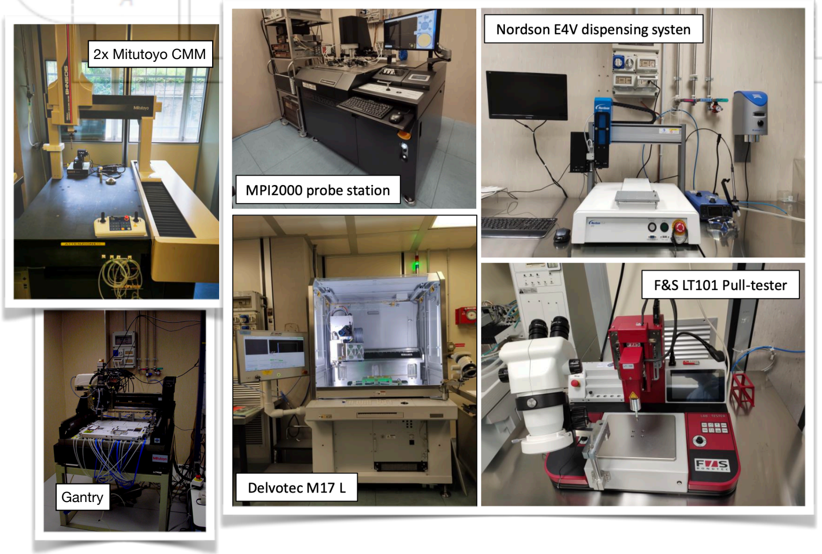
Infrastructure/Instrumentation

- Clean room of cleanliness quality ISO7
- Certification ISO14644-1obtained
- Total space available is > 100 m² , divided into two contiguous rooms (room A and room B)
- Temperature, humidity and particles concentration continuously controlled:
  - T = 17°C ÷ 28 °C with deviation of ±3°C during a day.
  - RH = 35% ÷ 65%, dew point at least 5 K below ambient temperature.
- ESD protection for all zones where the sensors and electronics are exposed.



Fully equipped with instrumentation for assembly (manually or automated) and characterisation:

MPI2000 probe station

Delvotec M17 L

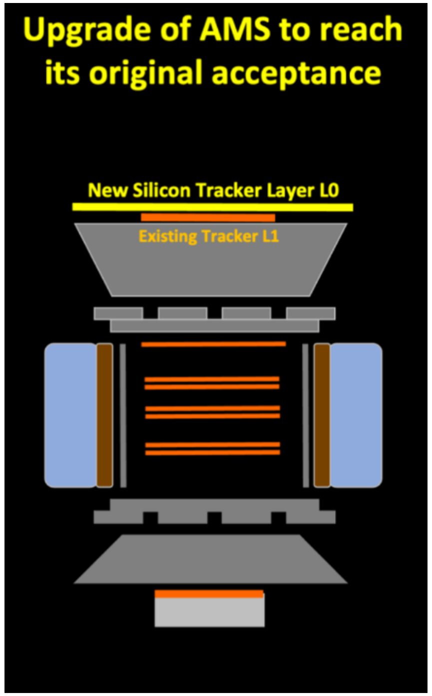
Mitutoyo metrology tables

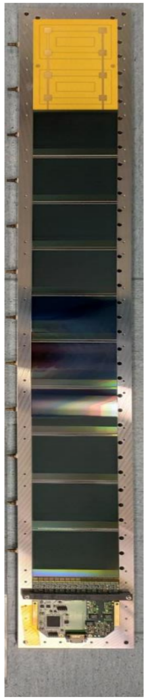
Nordson E4V dispensing system

…

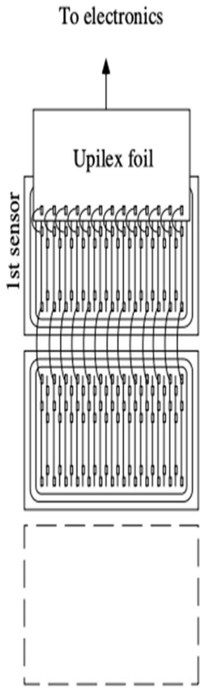
Activities

Space



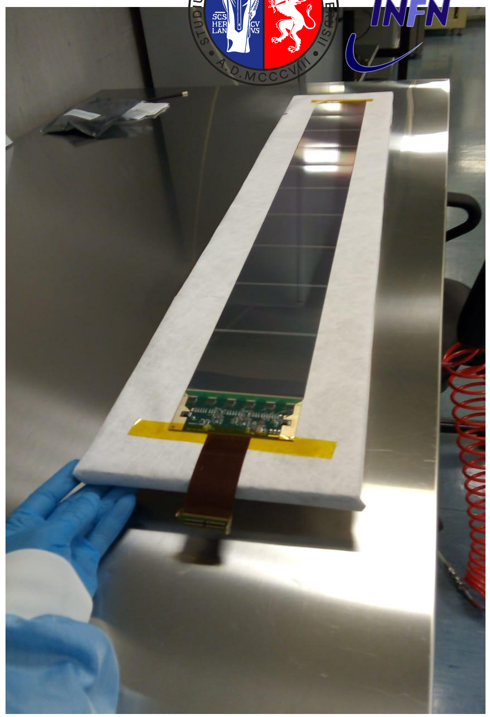


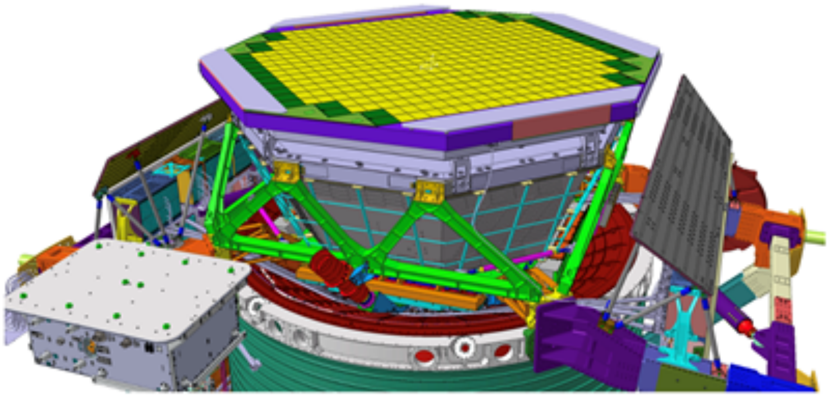
- 8 – 10 – 12 sensors
- 1024 channels
- pitch 27.5 (110) µm implant (readout)
- 0.3 W of power consumption
- ~ 10 µm resolution
- 0.3 c.u. charge (Z) resolution

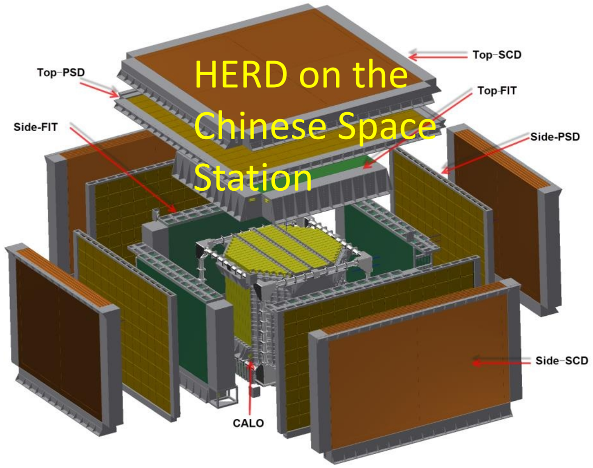


"daisy chain" of 10-12 sensors to reach ~ 1m long "ladders"

- 10 sensors
- 640 channels
- pitch 50 (150) µm implant (readout)
- 0.2 W of power consumption
- ~ 20 µm resolution
- 0.3 c.u. charge (Z) resolution

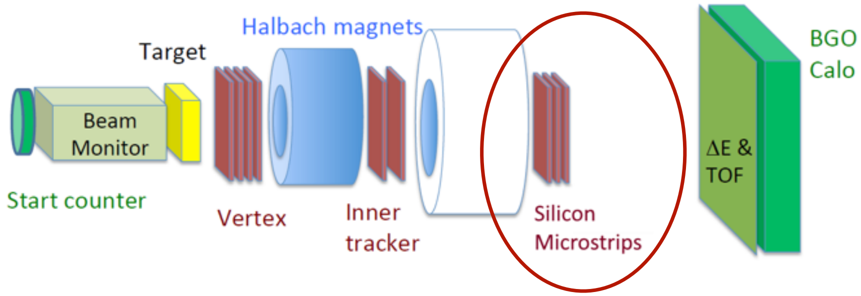






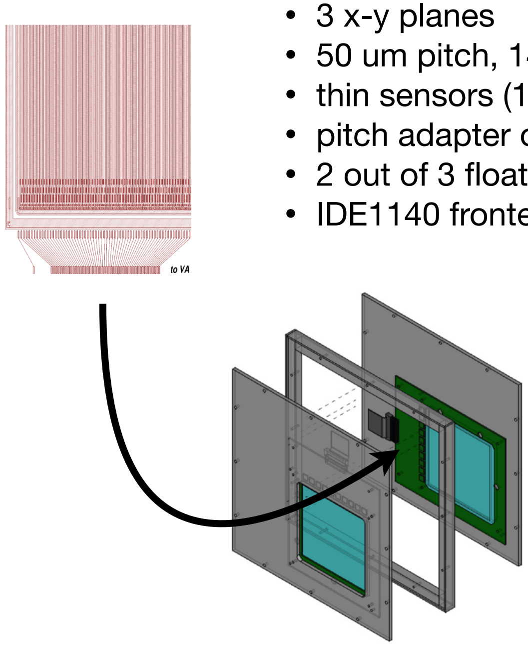
Nuclear Physics

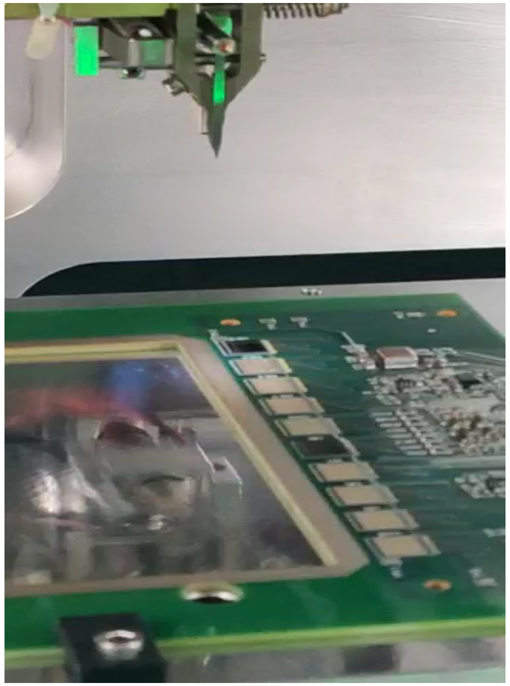
The main objective of the **FOOT** (**FragmentatiOn Of Target**) experiment is the measurement of the double differential cross-sections with respect to kinetic energy and emission angle of fragments produced in nuclear interactions at energies of interest for **hadrontherapy** (up to 400 MeV/u).

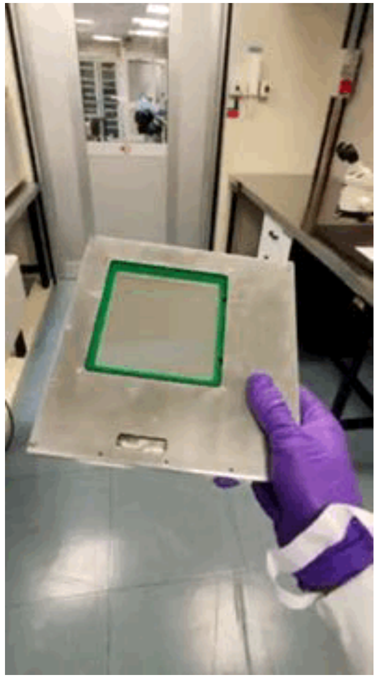


HPK silicon uStrip: 96 mm x 93 mm x 0.15 mm

- 3 x-y planes
- 50 um pitch, 14 um resolution
- thin sensors (150 um)
- pitch adapter on silicon
- 2 out of 3 floating strips
- IDE1140 frontend (64 multiplex analog RO)

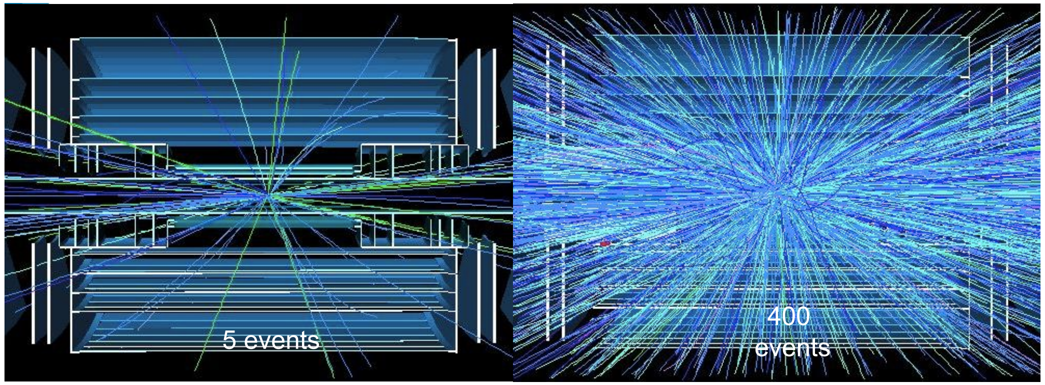


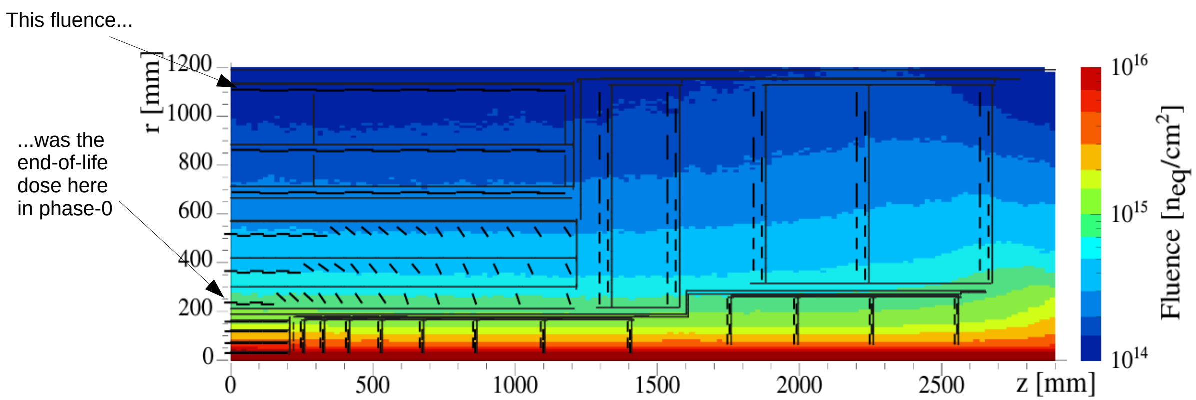




High Fluence - CMS

High Luminosity LHC: an hostile world



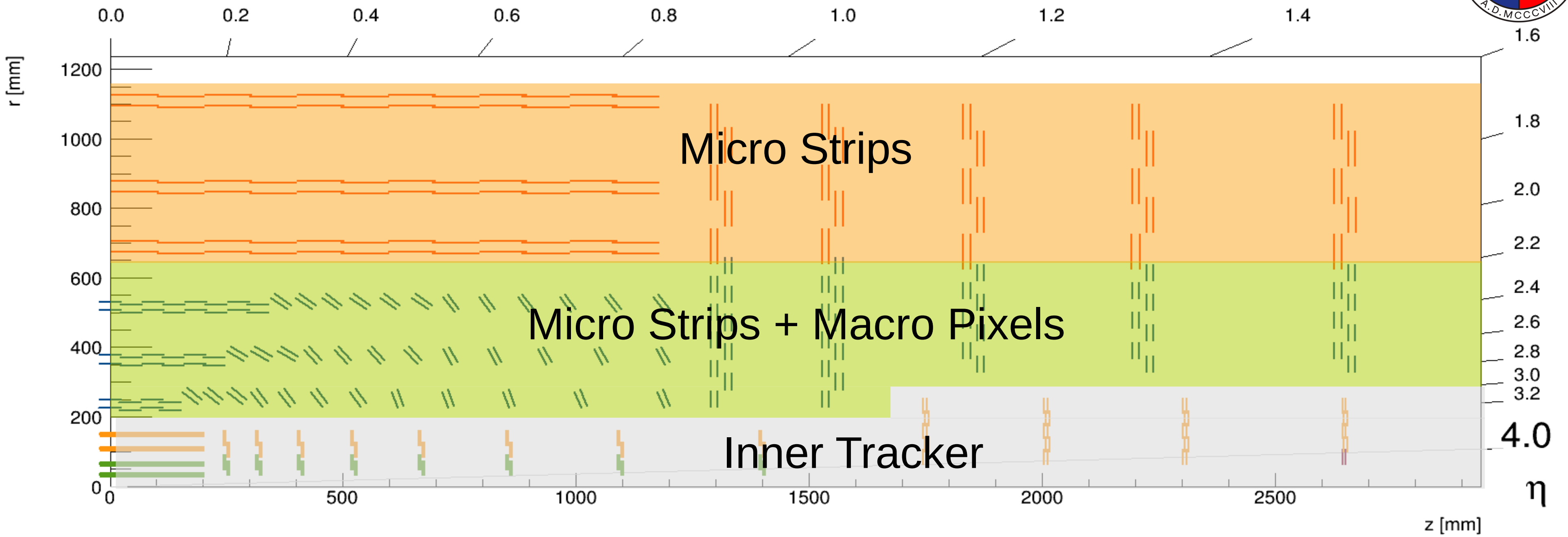


Radiation environment at HL-LHC will become increasingly hostile

Inner layers at few cm in radius will need to stand fluencies higher than 10^{16} MeV neutron equivalent

Even outer layers will receive $>10^{14}$ MeV, more than the innermost silicon strip layer of today's tracker after 10 years of LHC running

The Phase-2 Tracker



Key points:

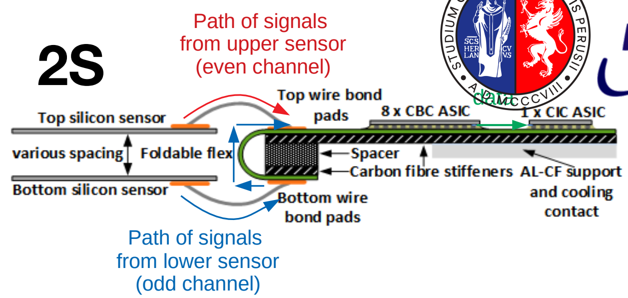
1) radiation hardness
2) L1 trigger integration
3) high granularity
4) low material budget

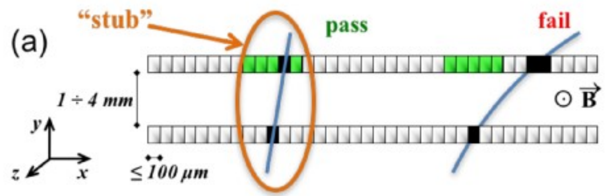
→

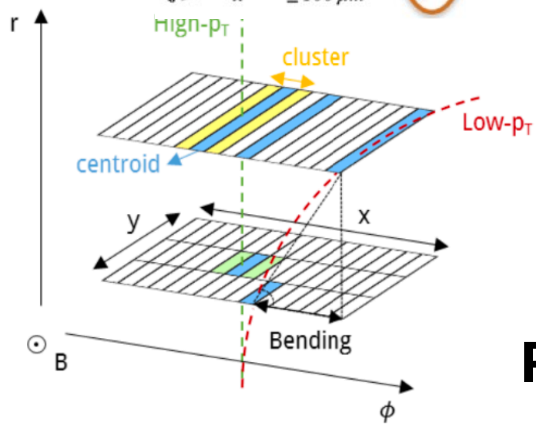
1) pixel 3D technology inner, thin outer sensors
2) fast readout and local reconstruction (PT module)
3) segmentation (macropixels outer)
4) tilted geometry

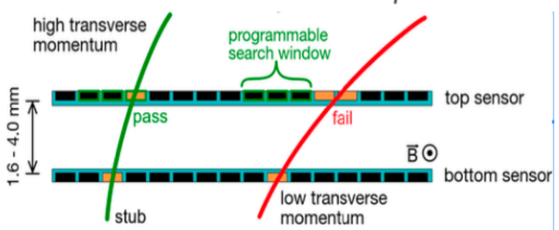
From hits to stubs

- Best exploitation of increased instantaneous luminosity delivered by HL-LHC
  → be more selective already at L1
  → solution: include tracks into L1 decision
- Central concept: pT modules
  - Two silicon sensors with small spacing in a module
  - Flex hybrid concept to get data from both sensors to one ASIC → select track "stubs"
- Different sensor spacing for different parts of the detector
- Acceptance window can be tuned



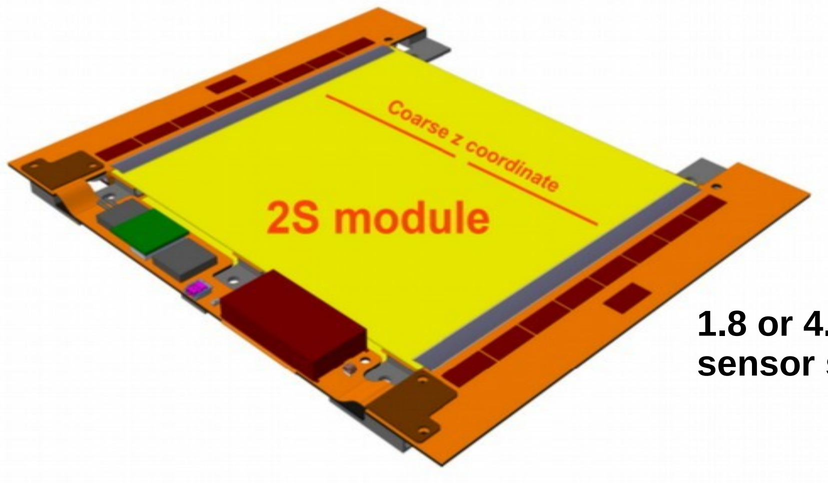




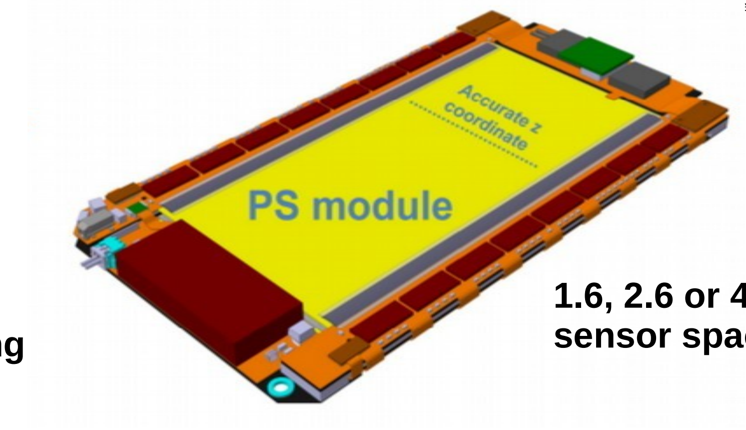


The price to pay is an increased module complexity…

Module types in the CMS Outer Tracker



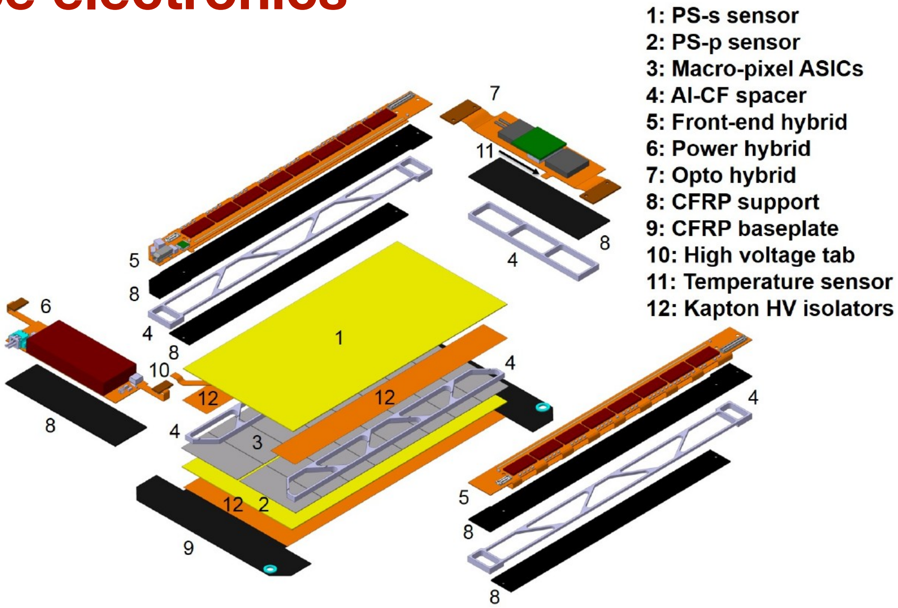
1.8 or 4.0 mm sensor spacing

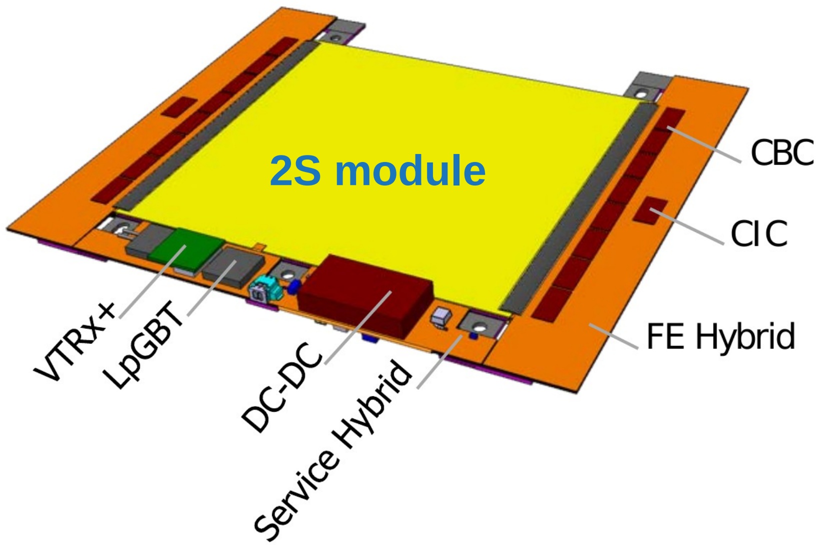


1.6, 2.6 or 4.0 mm sensor spacing

- Only two basic type of modules (compare to 15 in phase-0 CMS tracker)
- 2S Modules
  - Two strip sensors with 5 cm x 90 μm strips
  - Sensor is 10x10 cm^2 large → two sets of strips
- PS Modules → Module with one (Macro-)Pixel and one strip sensor
  - Sensor size: 5x10 cm^2
  - Strips: 2.5 cm x 100 μm
  - Macro Pixels: 1.5 mm x 100 μm

Service electronics





- Each module has frontend- and service hybrid(s)
- Frontend hybrid houses readout (CBC,SSA,MPA), and concentrator (CiC) chip
- Service hybrid(s) houses:
  - lpGBT (low-power Gigabit Transceiver, common development for HL-LHC experiments)
  - VL+ (Versatile Link Plus, common development for HL-LHC experiments)
  - DCDC converters (common development for HL-LHC experiments)
- **Module is the system** → no further card/aggregator between it and backend

CMS Tracker Phase-2: a massive production

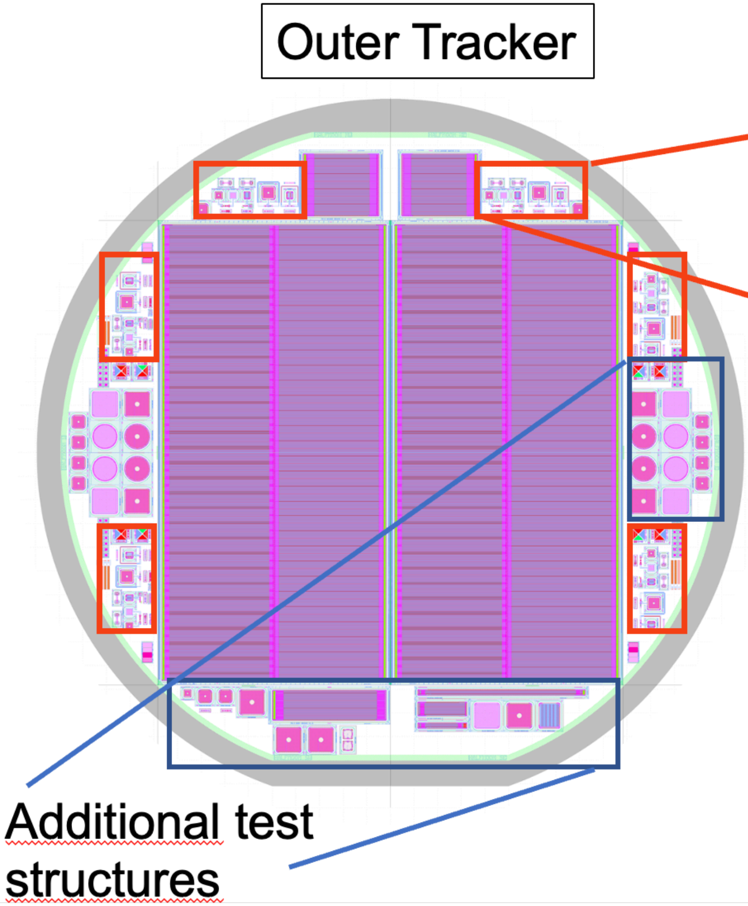
sub activities:

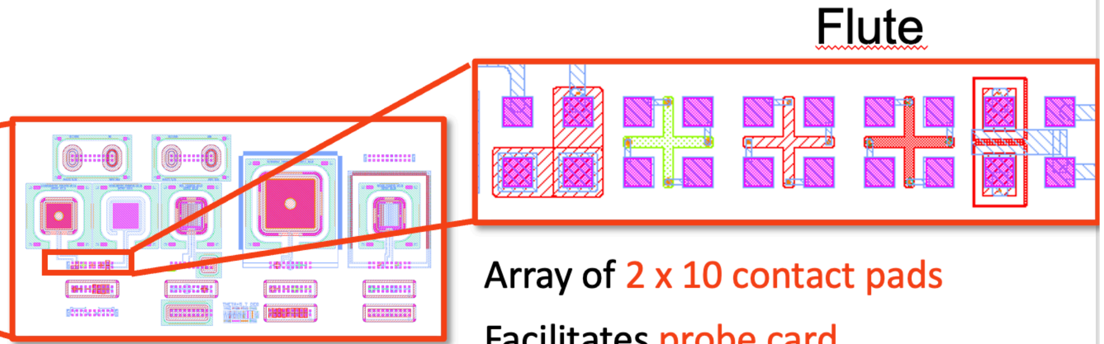
+ **sensor production qualification**
+ mechanical assembly
+ functional testing
+ powering
+ cooling

CMS T

sub a

Process Quality Control measurements





Array of 2 x 10 contact pads

Facilitates probe card measurements

I-V and C-V measurements on test structures

Access to most relevant process parameters

Substrate resistivity

Oxide quality

Si/SiO_2 Interface

Sheet resistances

Inter-strip resistance

CMS Tracker Phase-2: a massive production

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  qualification
+ **mechanical assembly**
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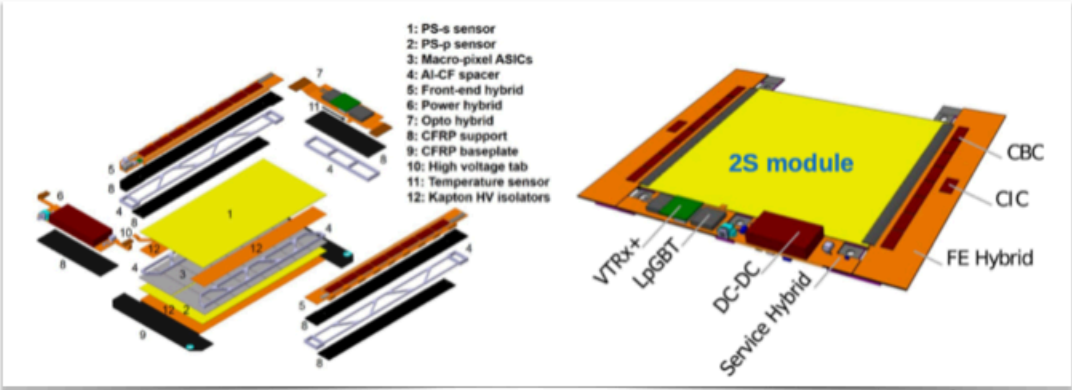
+ powering
+ cooling

CMS

Assembly

several components



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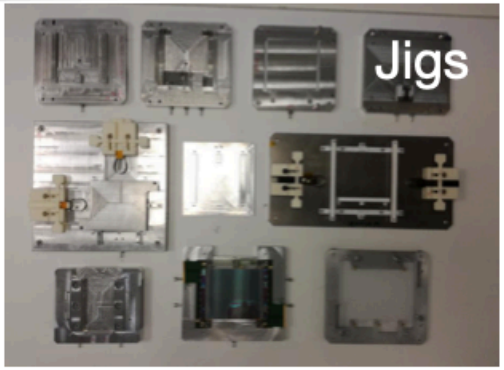
Tricky and complex assembly procedure due to the high requested mechanical precision.

A manual assembly procedure (Jig-based) is preferred to a fully automated one, even if the number of modules to be produced per CMS is high

Up to 10 Jigs per type and special handlings needed



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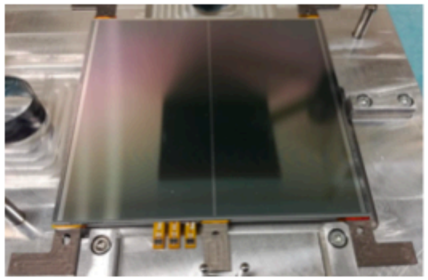
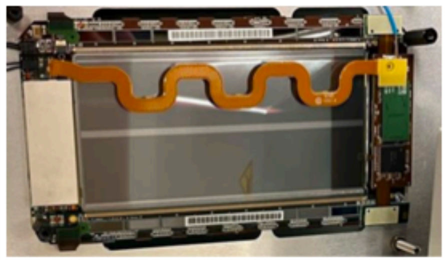
Complex Flow

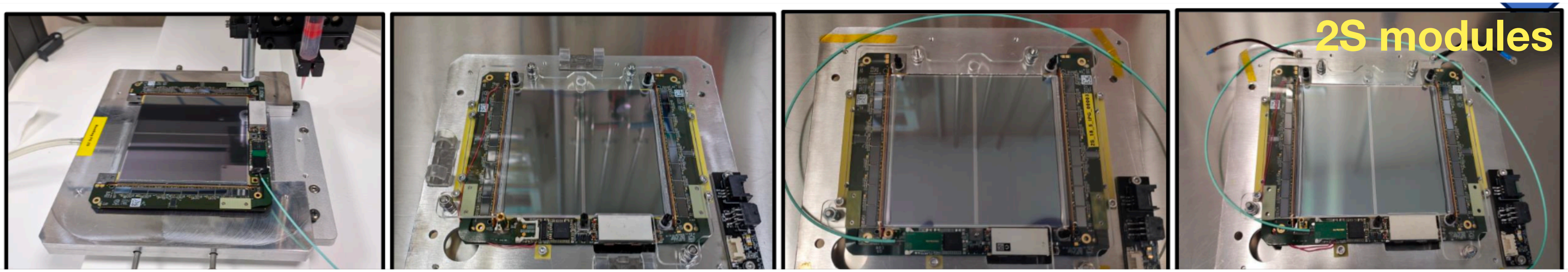


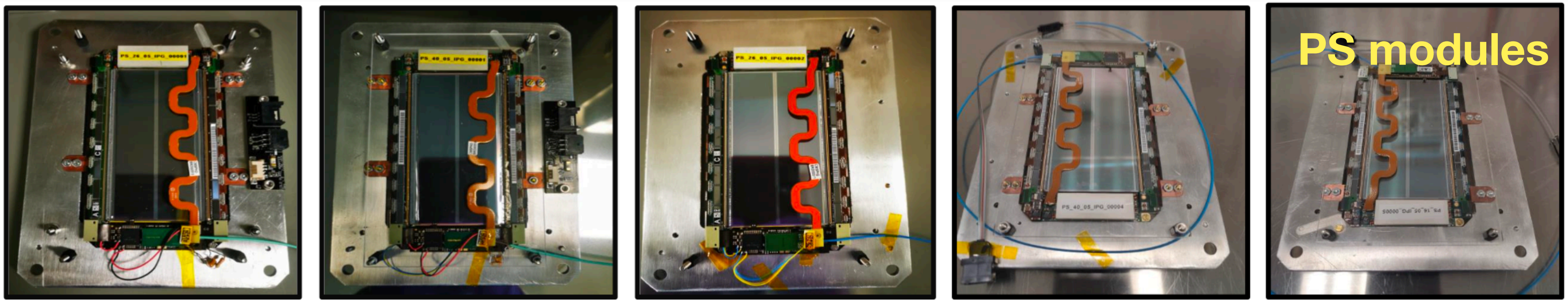


modules

CMS Tracker Phase-2: a massive production

Some example…





CMS Tracker Phase-2: a massive production

sub activities:

+ sensor production qualification
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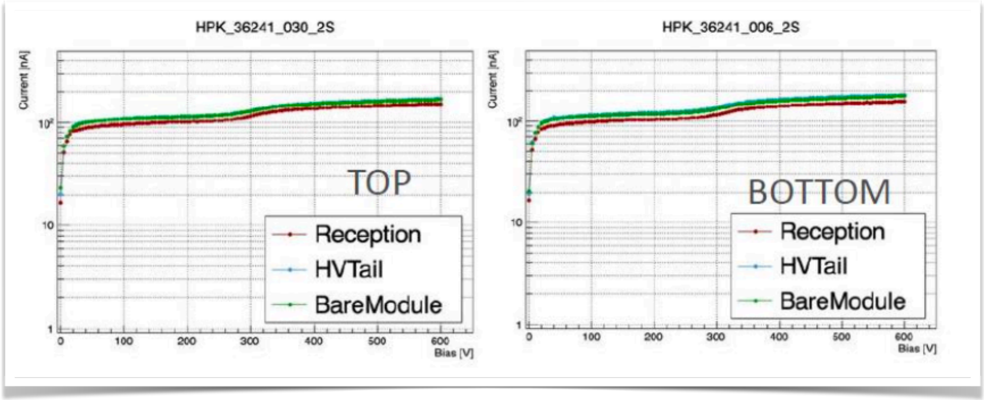
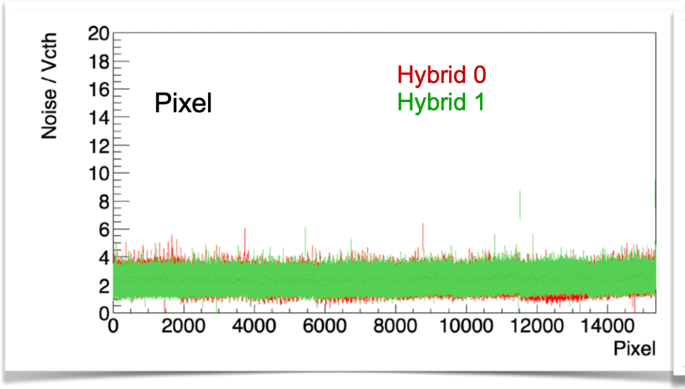
+ **functional testing**
+ powering
+ cooling

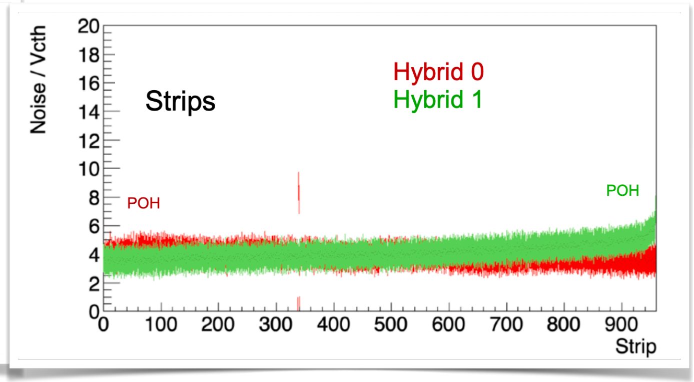
Module functional test

Stability: IV measurments on the sensors are done after each assembly step

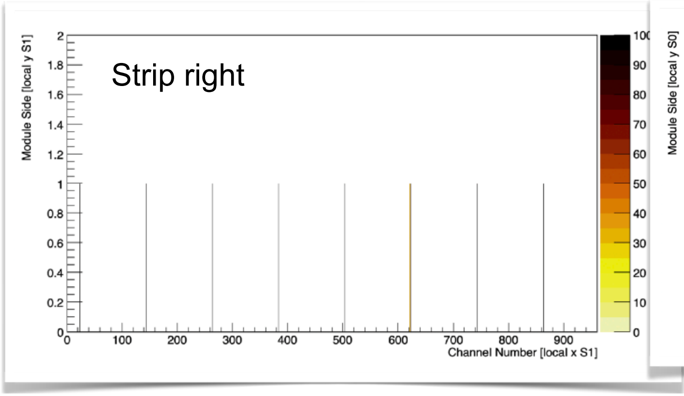


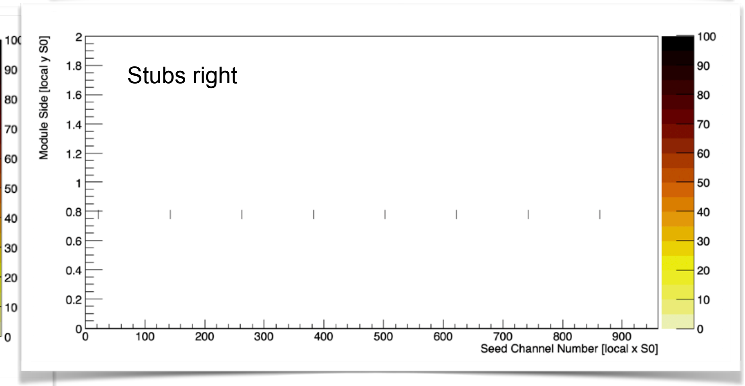
Currents analysis (light leaks, shilding…) and noise scan





L1/STUB -
full chain readout scan





CMS Tracker Phase-2: a massive production

sub activities:

+ sensor
  production
  qualification
+ mechanical
  assembly
+ functional testing
+ **powering**
+ cooling

CMS Tracker Phase-2: a massive production

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- + sensor production qualification
- + mechanical assembly
- + functional testing
- **+ powering**
- + cooling

system test

1 - Desktop PC

- Not high hardware requirements
  - P4 2000 (minimum), 4 GB RAM, 500 MB HD
- Connection to machine through ethernet cable
  - If connection to Internet is needed, the PC must have wifi module or additional ethernet port
- Run the software CEETIS
  - Provided by the machine manufacturer
  - Works on Windows (Vista to 10)
  - Used both as program editor and user interface for performing tests.

2 - Weetech Testsystem W 434

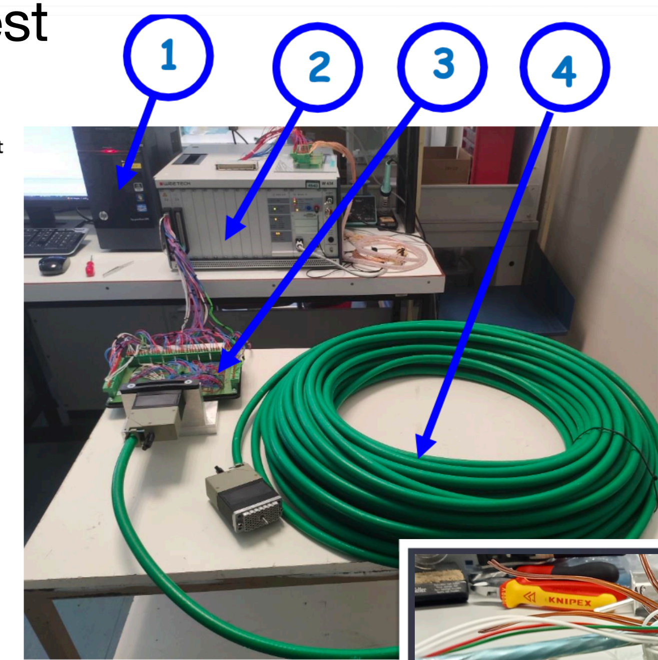
- LV-DC Generator
  - Voltage: 48 Vdc/max 20W
  - Current: Programmable 10mA to 1A
  - Application: Continuity, shorts, resistance, components test
- HV-DC Generator
  - Voltage: Programmable to 1.5 KVdc
  - Current: 1.95 mA
  - Application: Insulation tests

3 - Adapter board(s)

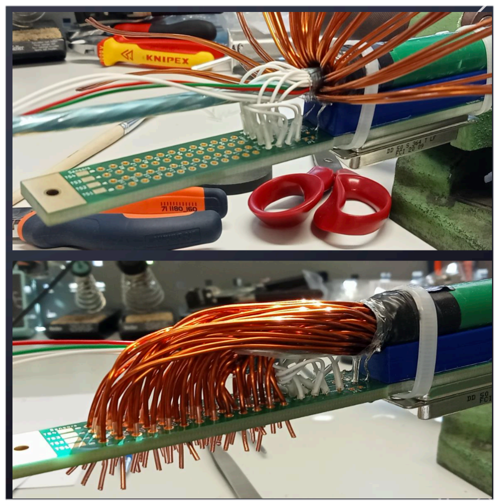
- Convert the pin-matrix on the cable connectors to the pins on the machine front panel.

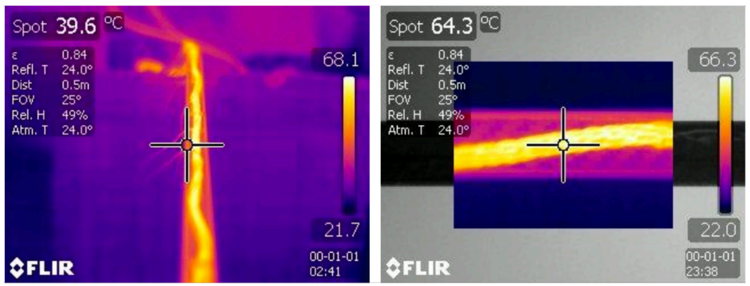
4 - Cable under test

- Octopus cab



connectors





thermal test

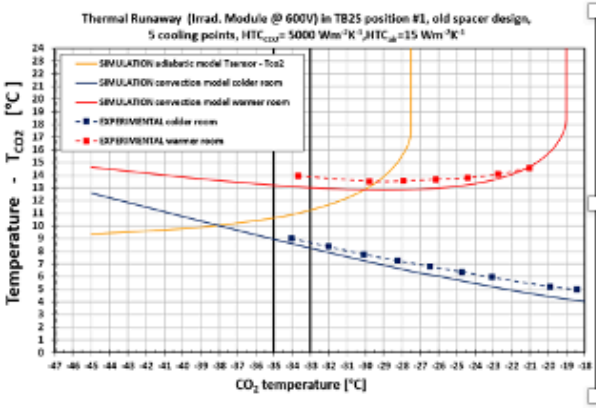
CMS Tracker Phase-2: a massive production

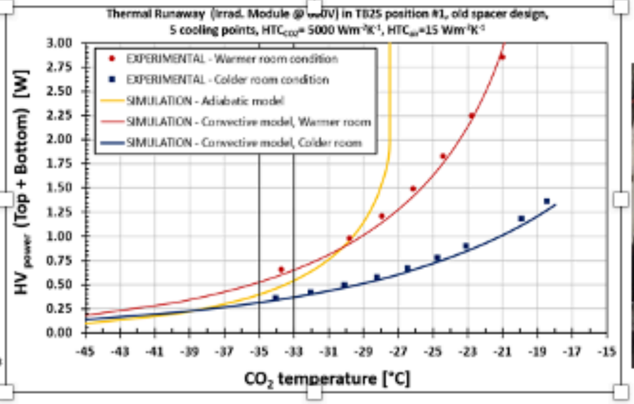
sub activities:

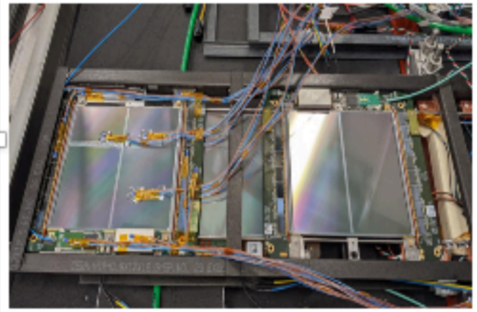
- \+ sensor
  production
  qualification
- \+ mechanical
  assembly
- \+ functional testing
- \+ powering
- **+ cooling**

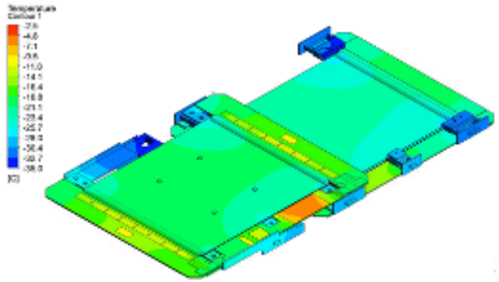
Tracker module thermal studies

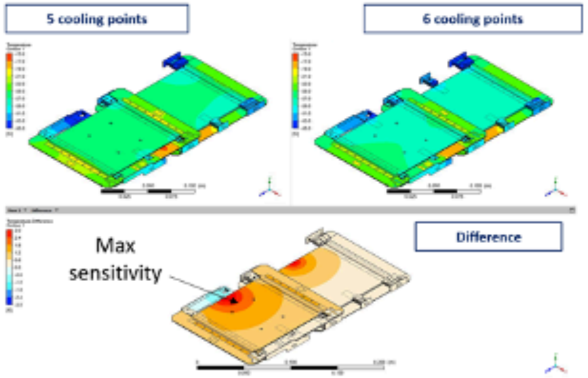
- Experimental validation
  - Experimental setup at CERN and Aachen
  - Good match between tests and simulations (±1°C on temperature)
  - Environmental conditions effect on modules thermal balance

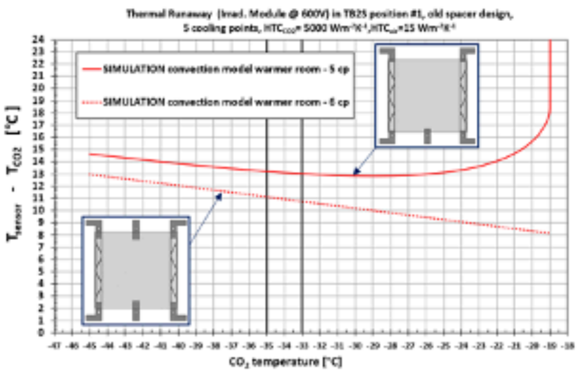


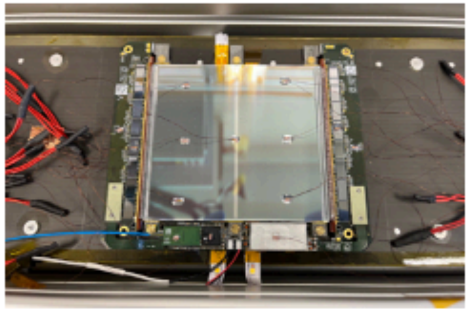


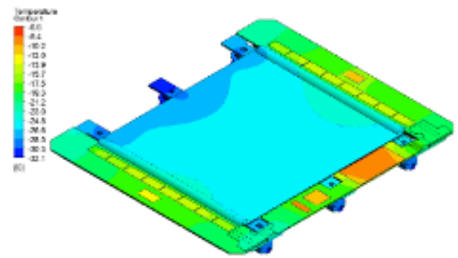










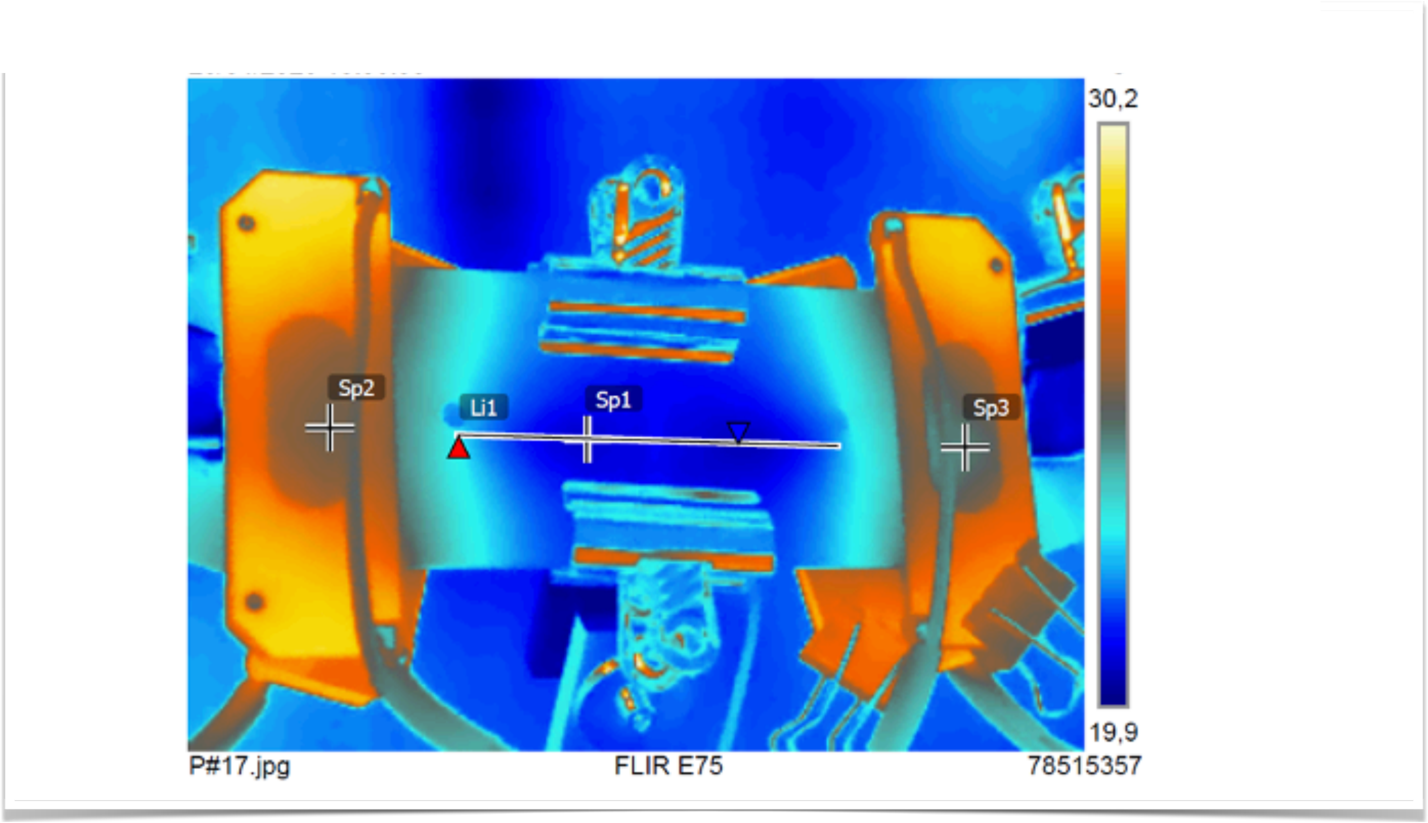


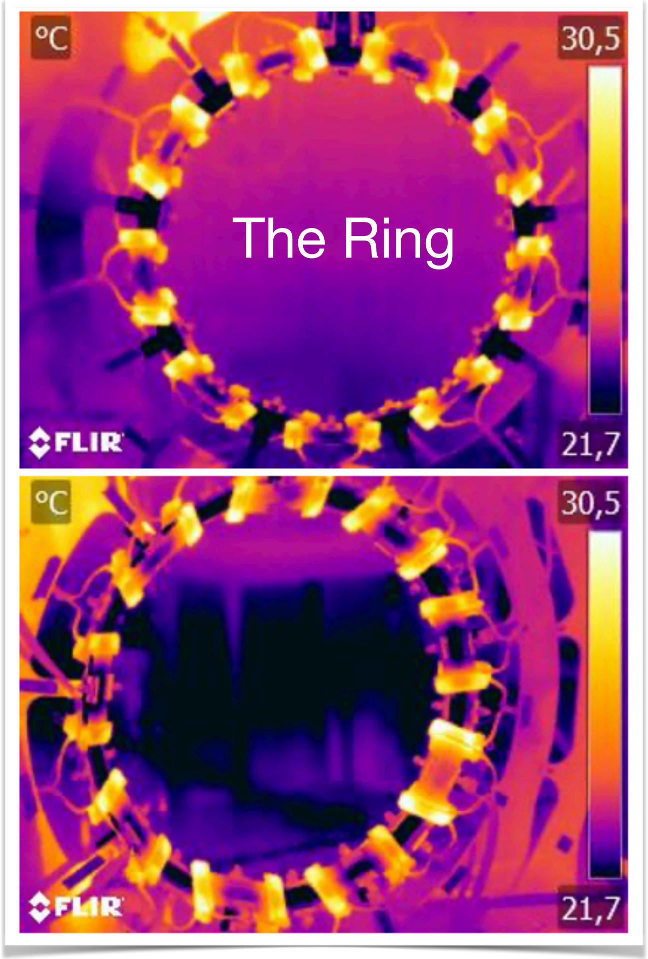
Thermography of integration structures

The thermographic survey can give us a global picture of the ring and specific thermal field of each position/dummy module

For each ring a set of IR picture with all dummy modules and global picture will be acquired

The IR pictures can be elaborated to check temperature trends along the line





2S module spin-off -> MUonE experiment

2S modules have been selected to provide a functional solution for MUonE experiment, for several reasons.

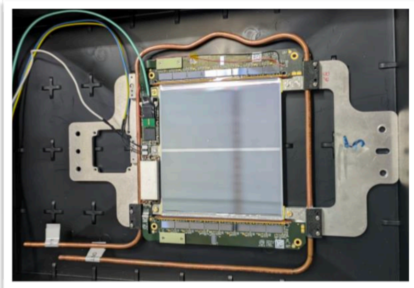
Present tracking stations are equipped with 6 2S modules each, providing 3 independent measurements of the coordinates

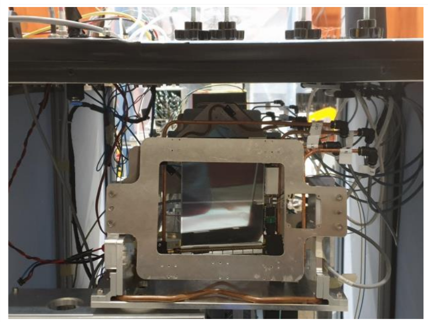
Resolution needed by MUonE is at limit of 2S design capability, tilted modules to increase resolution

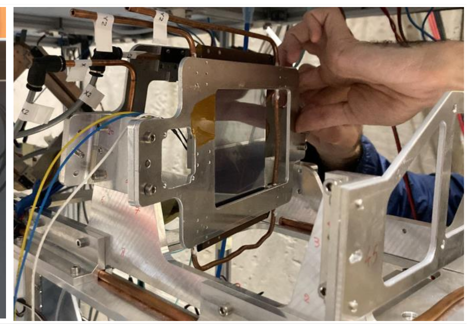
Signals from modules are reduced back from stub to a pseudo-hit information

Material budget contribution to multiple scattering could be a limitation for resolution

During last test run 2S modules have been used to construct 2 tracking station, readout and stability have been successfully explored



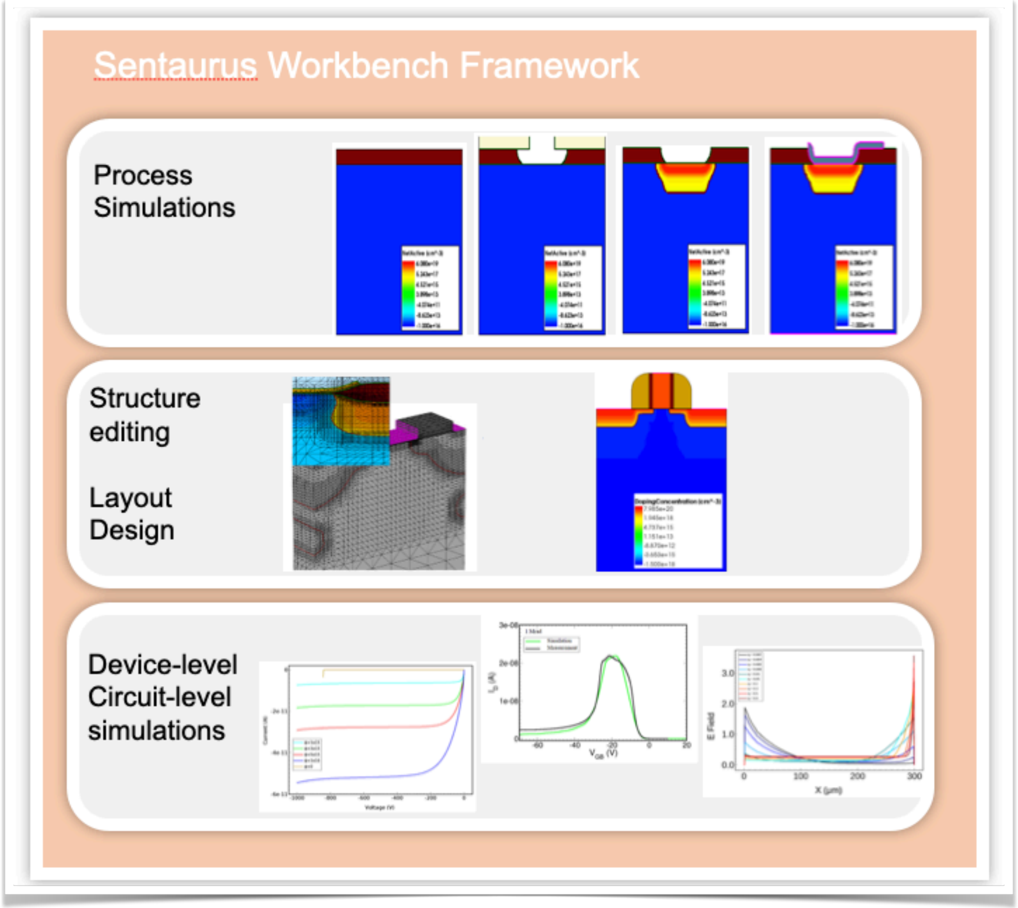




Specific studies on technology design and optimization, an hint for future experiments and applications?

1) Radiation Damage Models
2) Low Gian Avalanche Detector
3) a-SI:H

The Technology-CAD modelling approach



- TCAD simulation tools solve fundamental, physical partial differential equations, such as **diffusion** and **transport equations** for discretised geometries (finite element meshing).
- This deep **physical approach** gives TCAD simulation **predictive** accuracy.
- **Synopsys© Sentaurus TCAD**

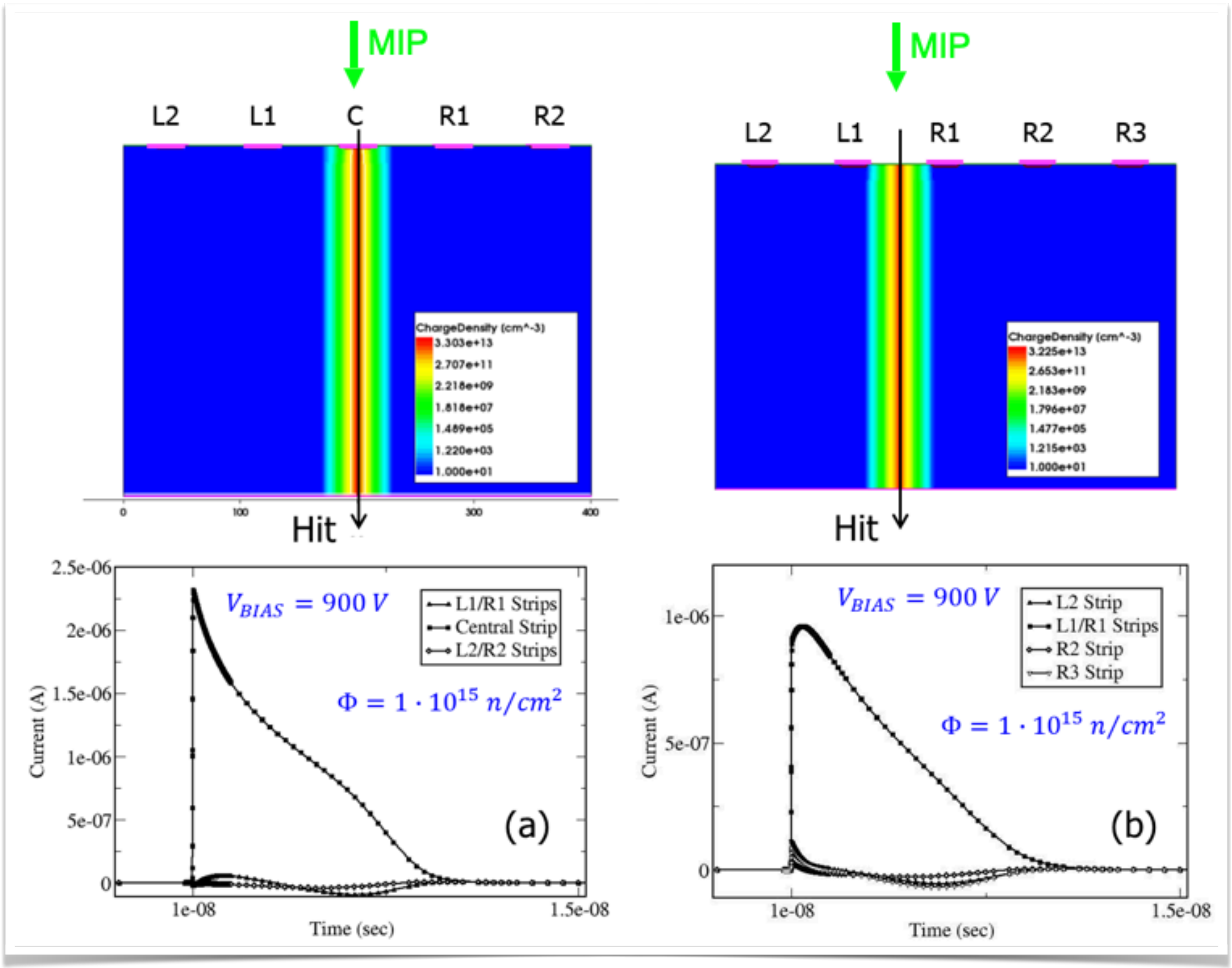
$$\begin{cases} \nabla \cdot (-\varepsilon_s \nabla \varphi) = q\left(N_D^+ - N_A^- + p - n\right) & \text{Poisson} \\ \dfrac{\partial n}{\partial t} - \dfrac{1}{q} \nabla \cdot \vec{J}_n = G - R & \text{Electron continuity} \\ \dfrac{\partial p}{\partial t} + \dfrac{1}{q} \nabla \cdot \vec{J}_p = G - R & \text{Hole continuity} \end{cases}$$

$$\vec{J}_n = -q\mu_n n \nabla \varphi + q D_n \nabla n$$

$$\vec{J}_p = -q\mu_p p \nabla \varphi - q D_p \nabla p$$

Radiation damage modelling

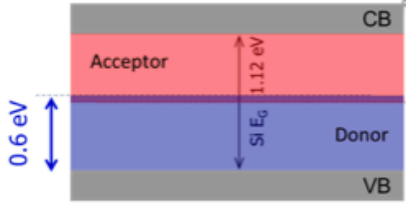
- Modern TCAD tools offer a wide variety of approaches, characterized by different combinations among physical accuracy and comprehensiveness, application versatility and computational demand
  -> **mixed-mode** approaches can be efficiently followed.
- Within a **hierarchical approach**, increasingly complex models have been considered, aiming at balancing complexity and explainability.
- A number of different physical damage mechanisms actually may interact in a non-trivial way. Deep understanding of physical device behaviour therefore has the utmost importance, and device analysis tools may help to this purpose.
- **Bulk and surface** radiation damage have been taken into account by means of the introduction of deep-level radiation-induced traps whose parameters are physically meaningful and whose experimental characterisation is feasible.

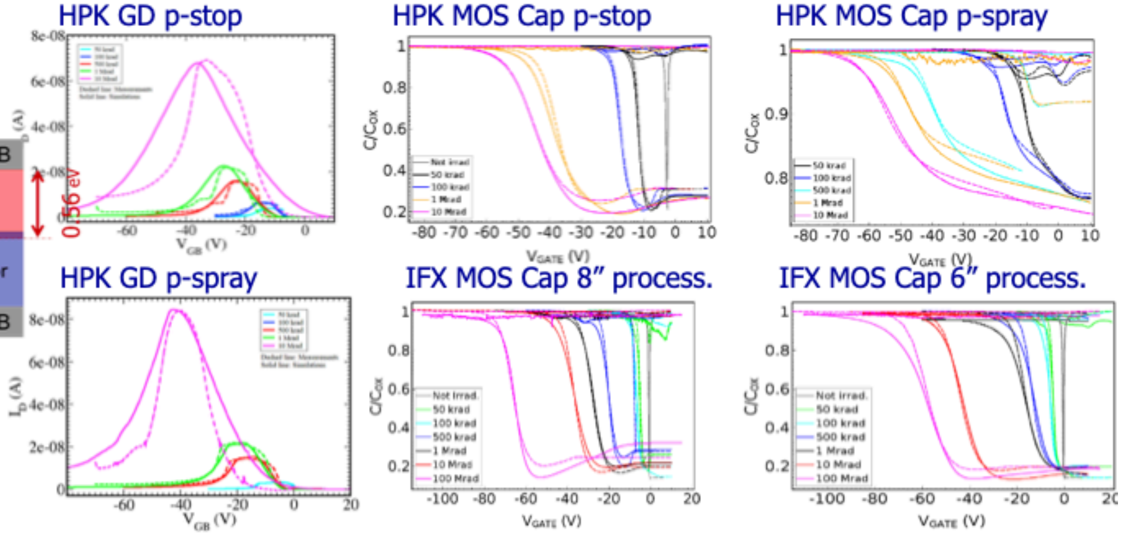


new “Univ. of Perugia” numerical model

√ Surface damage (+ Q_{OX})

Type	Energy (eV)	Band width (eV)	Conc. (cm^{-2})
Acceptor	$E_C \le E_T \le E_C$-0.56	0.56	$D_{IT} = D_{IT}(\Phi)$
Donor	$E_V \le E_T \le E_V$+0.6	0.60	$D_{IT} = D_{IT}(\Phi)$



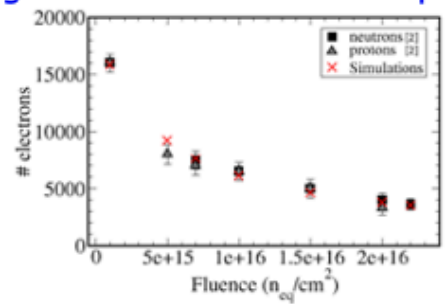


√ Bulk damage

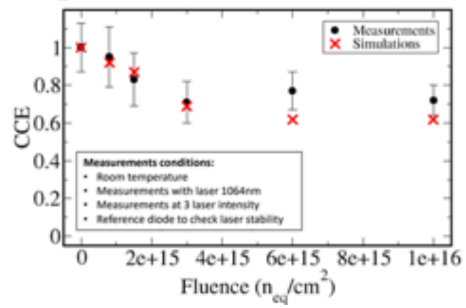
Avalanche ON: Van Overstraeten–De Man (default)

Type	Energy (eV)	η (cm^{-1})	σ_n (cm^2)	σ_h (cm^2)
Donor	E_C - 0.23	0.006	2.3×10^{-14}	2.3×10^{-15}
Acceptor	E_C - 0.42	1.6	1×10^{-15}	1×10^{-14}
Acceptor	E_C - 0.46	0.9	7×10^{-14}	7×10^{-13}

Charge Collection for silicon strips.



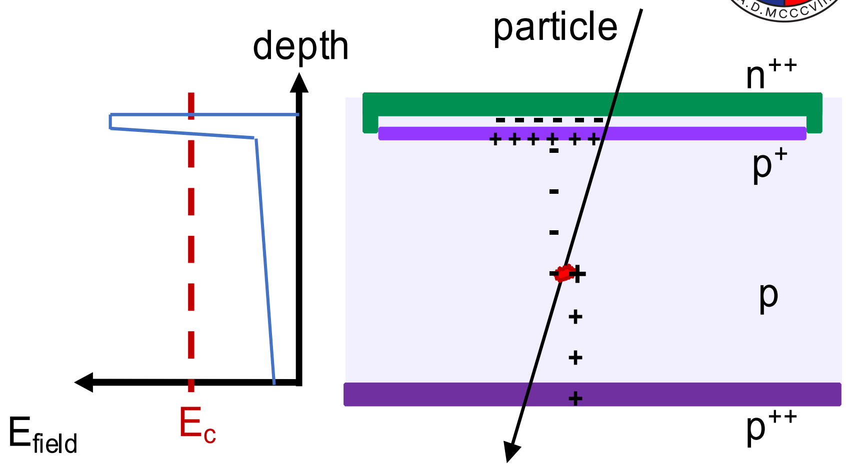
Charge Collection for PiN diodes



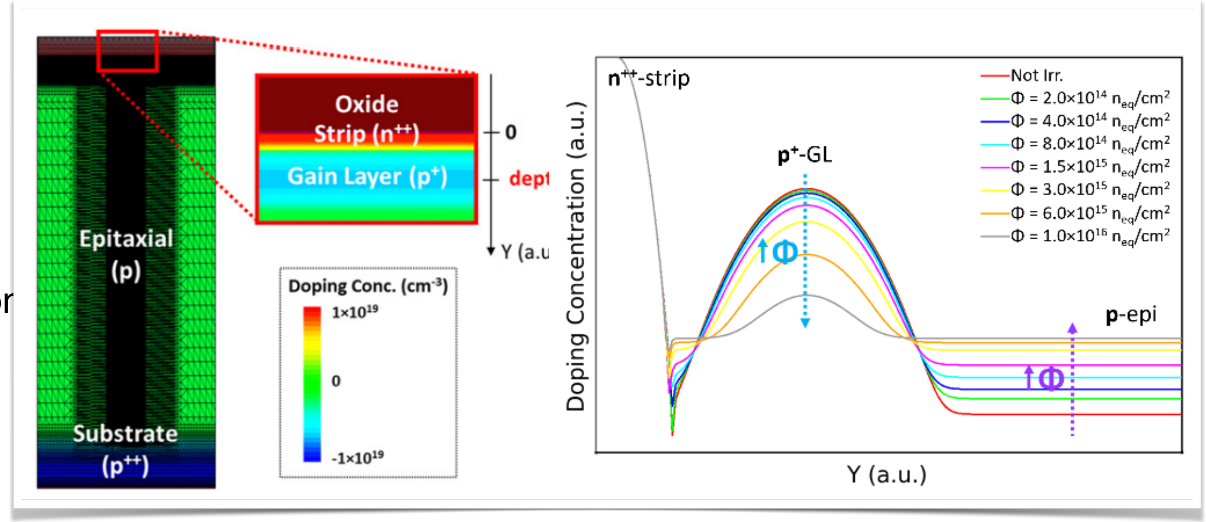
AIDA 2020

Low Gain Avalanche Diodes

- **Low-Gain Avalanche Diode (LGAD)**
  - **n-in-p silicon** sensors
  - Operated in **low-gain regime**
  - Critical electric field ~ 20 – 30 V/μm
  - Good candidates for **4D tracking**
  - **Mitigation of the radiation damage effects by exploiting the controlled charge multiplication mechanism.**



Layout and **doping profile**

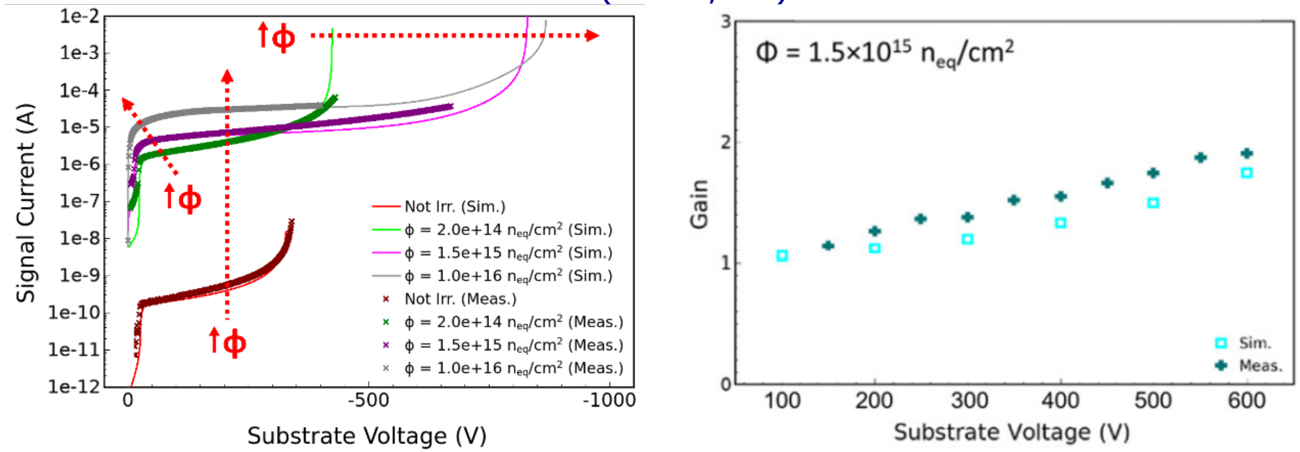


- **Advanced TCAD** modeling
  - **Radiation damage effects** model implementation
  - Accounts for the acceptor removal mechanism which deactivates the p+-doping of the gain layer with radiation
  - Electrical behavior **prediction/ performance optimization** up to the highest fluences.

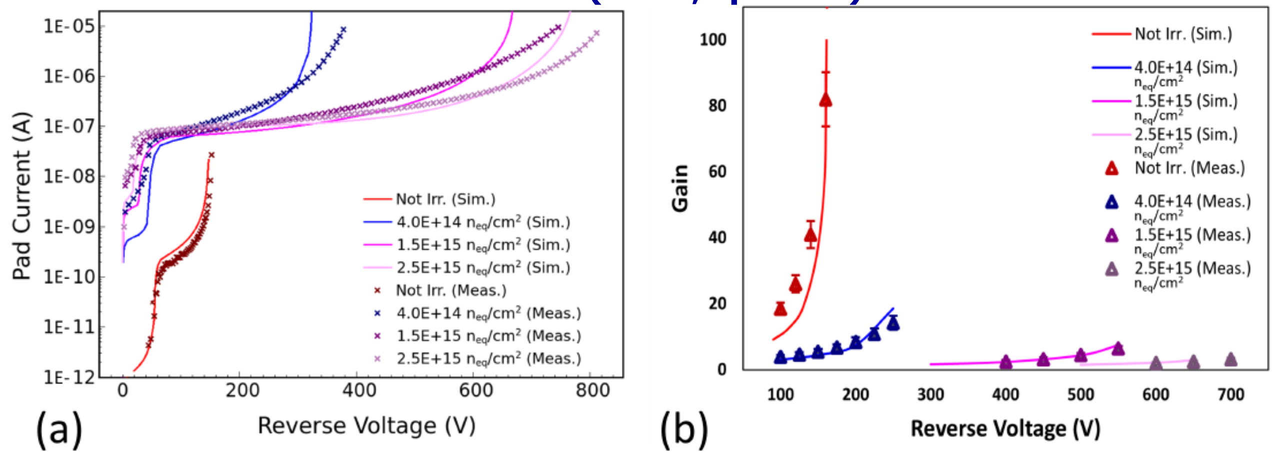
LGAD: Electrical behavior investigation

- **FBK LGADs** (UFSD2, W1)
  - 55 µm thick
- **HPK LGADs** (HPK2, split 1-2)
  - 50 µm thick
- Simulations-Measurements comparison TCAD settings:
  - ”PerugiaModDoping”
  - Temperature sets as per experimental measurements (RT not-irrad, 248 K irrad).
  - Electrical contact area 1mm².
  - Frequency 1-2 kHz for C-Vs as per experimental measurements.

FBK LGADs (UFSD2, W1)

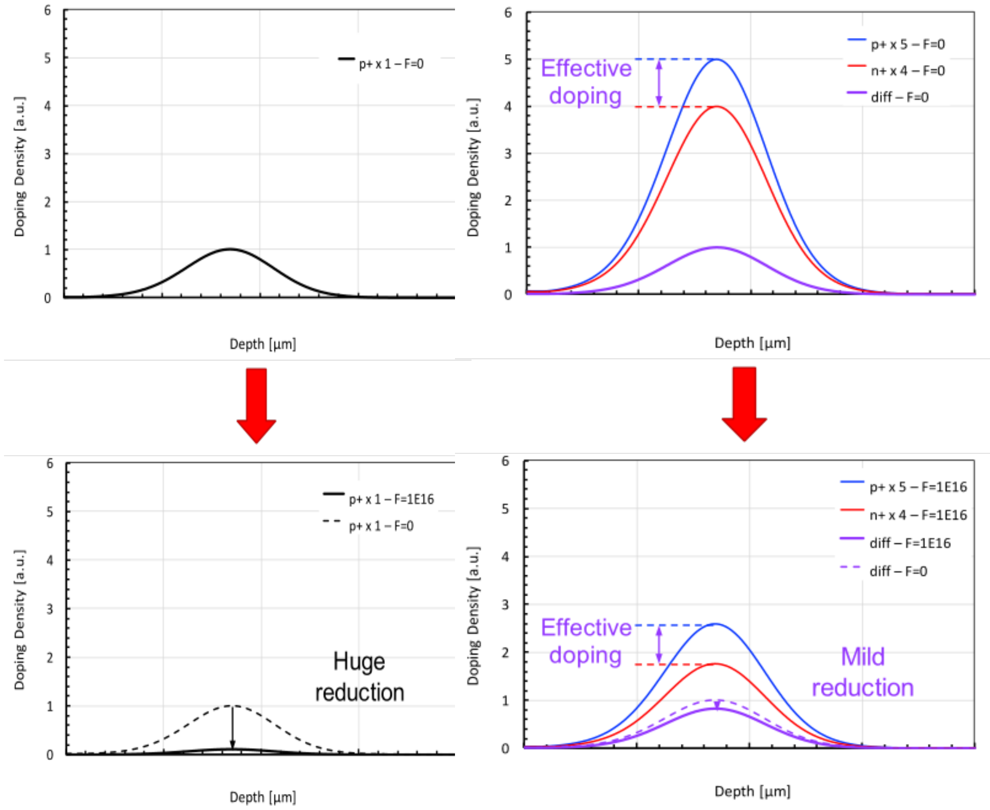


HPK LGADs (HPK2, split 1-2)



Compensated LGAD: innovation for extreme fluences

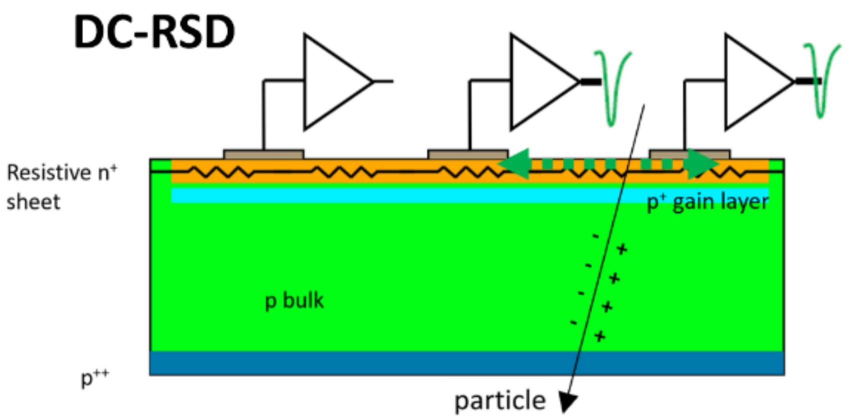
- **Goal**: extreme fluences **Φ =5·10^{17} n$_{eq}$/cm^2**
- In **standard LGAD**
    - acceptor removal mechanism ? **Φ >1–2·10^{15} n$_{eq}$ /cm^2** lose the multiplication power and behave as **standard n-in-p sensors.**
- Overcome the present limits above extreme fluences:
    - **saturation** of the radiation damage effects above 5·10^{15} n$_{eq}$/cm^2
    - the use of **thin** active substrates (20 – 40 um)
    - **extension** of the **charge carrier multiplication** up to 5·10^{17} n$_{eq}$/cm^2
- Use the **interplay** between **acceptor** and **donor** removal to keep a constant gain layer active doping density.
  Compensated LGAD: Technology under development (FBK EXFLU1 R&D)
- Many unknowns:
    - donor removal coefficient,
    - interplay between donor and acceptor removal (cD vs cA)
    - effects of substrate impurities on the removal coefficients



Standard LGAD design

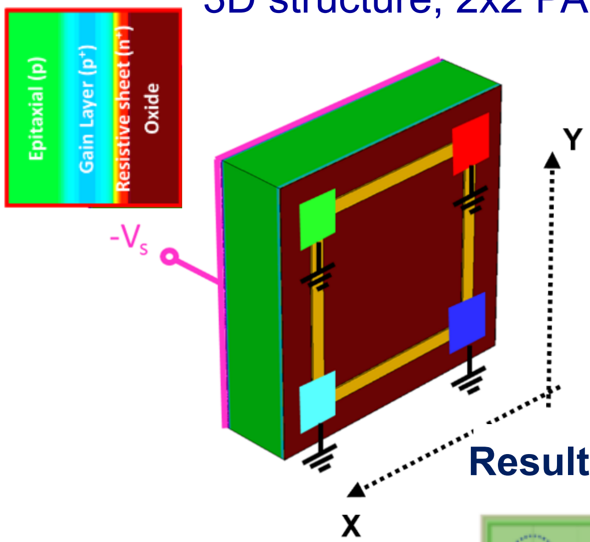
Compensated LGAD

Resistive Silicon Detector: (AC-) DC-RSD



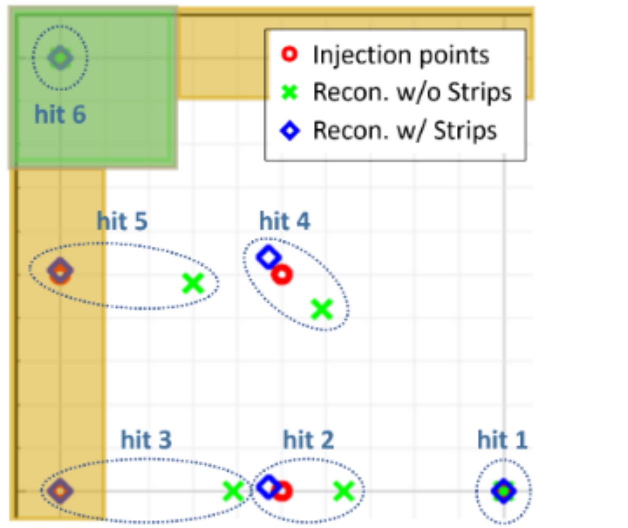
- This design is presently under development by FBK.
- The main advantage of the DC-RSD design is to limit the signal spread;
- A promising solution to simultaneously meet all the specifications required for the next generation of colliders;
- Evaluation of different layouts and technologies for future DC-RSD production using TCAD tools;
- Few microns and few tens of ps resolution

3D structure, 2x2 PADs => LGAD



- **BACK** → V_s = -110 V
- **PAD1** → V_1 = 0 (**GND**)
- **PAD2** → V_2 = 0 (**GND**)
- **PAD3** → V_3 = 0 (**GND**)
- **PAD4** → V_4 = 0 (**GND**)

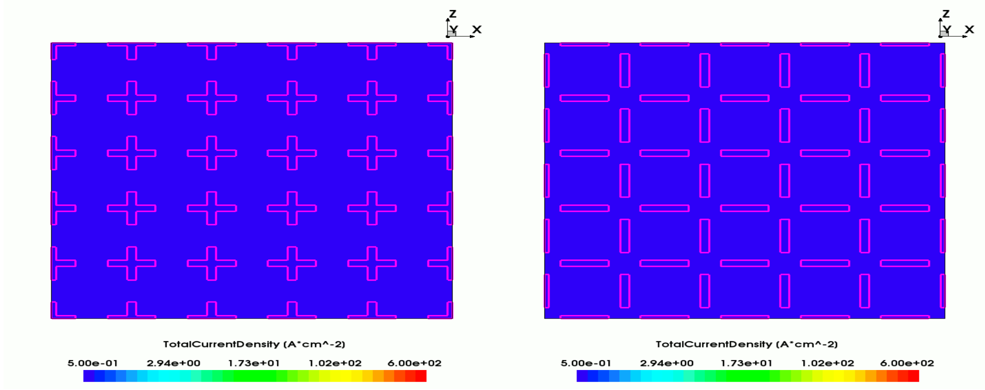
Results from *TCAD* simulations



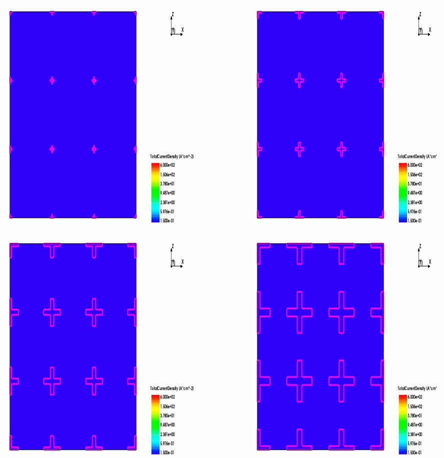
Charge sharing and signal confinement

- Investigation of the **signal confinement** within the TCAD environment.
- Minimum Ionizing Particle (**MIP**): various hit points considered.
- Different **pad geometries**
  - Cross or bar-shaped;
  - Better confinements in larger pads;
  - Error in reconstruction by associating any point covered by metal with the center of the pad;
- Need small, circular-shaped electrodes and strategy to confine the signal (e.g., trenches);

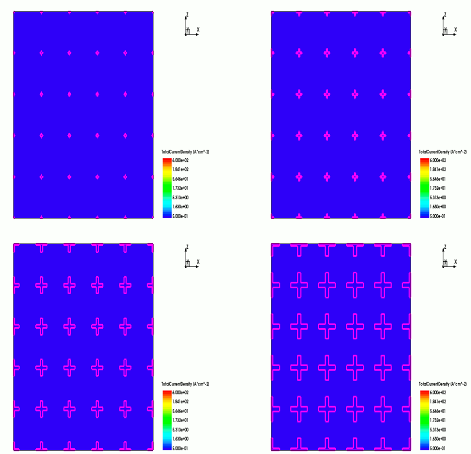
Cross- vs bar-shaped pads



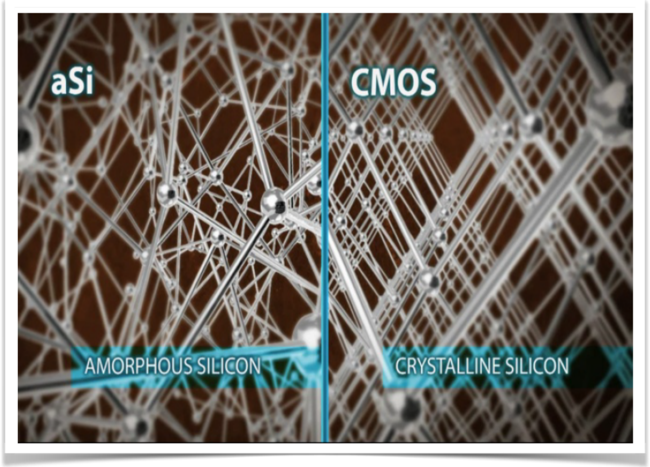
Single hit point



Three hit points

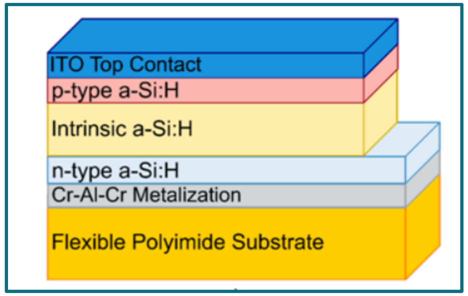


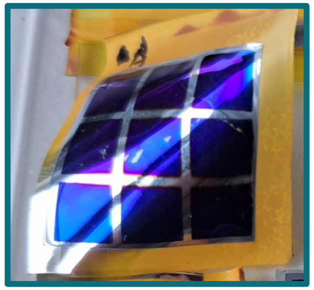
a-Si:H - Haspide

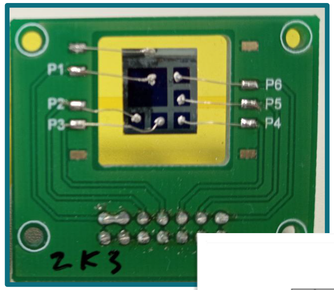


Intrinsically rad-hard - **Dosimetry and beam monitoring applications.**

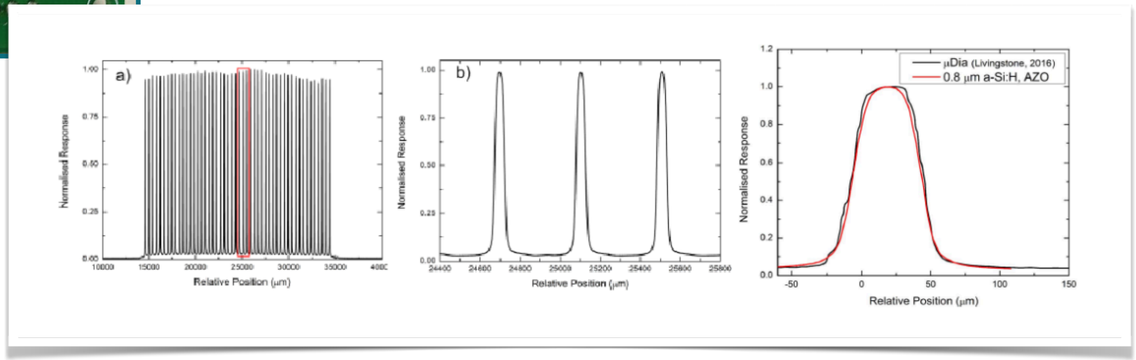
Thin a-Si:H (1- 100 um) ionizing radiation detectors deposited over **thin** plastic/**flexible** supports, even on **wide area** to be used for:







- Beam monitoring of linacs and other types of accelerators;
- Detection of radiation bursts in space;
- Neutron detection via conversion.



Very small beam profile measurements (≈ 50 um), performed at 10 cm depth in a solid water phantom compared to reference. 0.1 us integration time

Conclusions

Several activities have been presented, exploiting the experimental center capabilities in terms of study, R&D and construction

Different experimental phase for different activities: detector control in present CMS, construction for Phase-2 and R&D for future

Next generation experiments are expected to face extreme radiation environment (hadronic machine with high luminosity) and/or abilitate 4D tracking, very high space and time resolutions (electromagnetic scenario, precision physics)

LGAD studies are very promising and are expected to provide innovative solution for future tracking systems