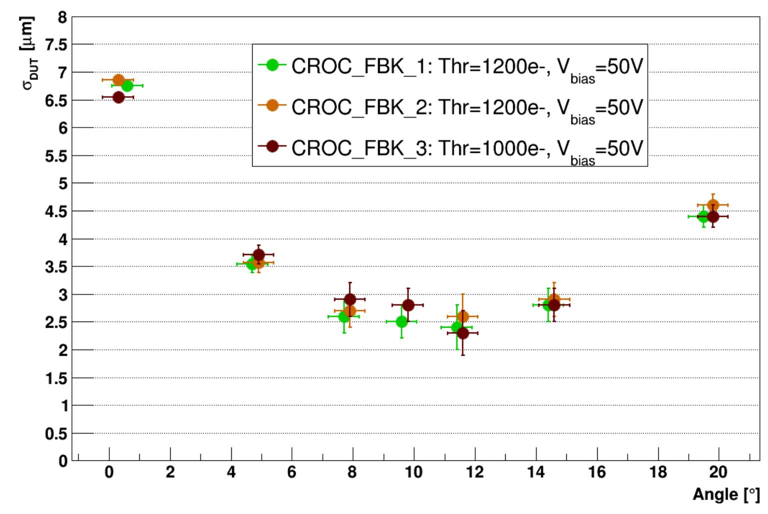
3D silicon pixel sensors for the CMS experiment upgrade

Davide Zuolo

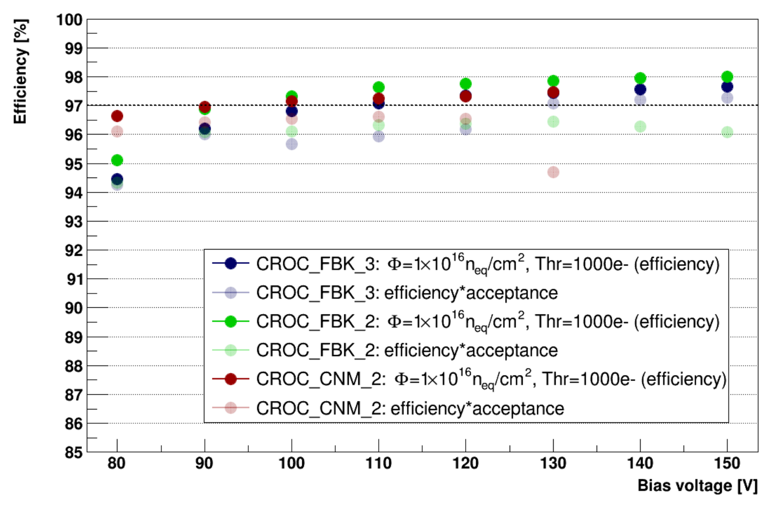
University of Colorado - Boulder

On behalf of the CMS Tracker group

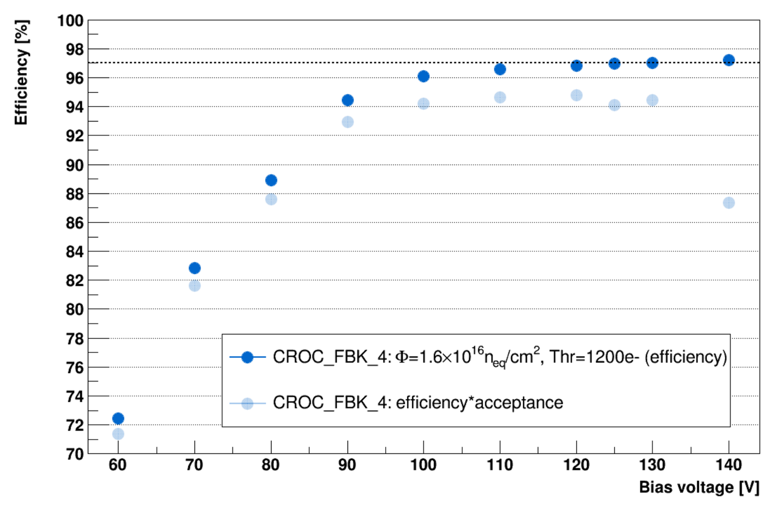
Test beam characterisation of single chip assemblies has been carried out at CERN SPS (120 GeV pions), Fermilab FTBF (120 GeV protons) and DESY (5.2 GeV electrons). Fresh and irradiated 3D sensors bonded to the CROC_v1 ROC have been studied in 2022 and 2023. 2024 beam time will be employed to study the performance of irradiated 1x2 3D modules.



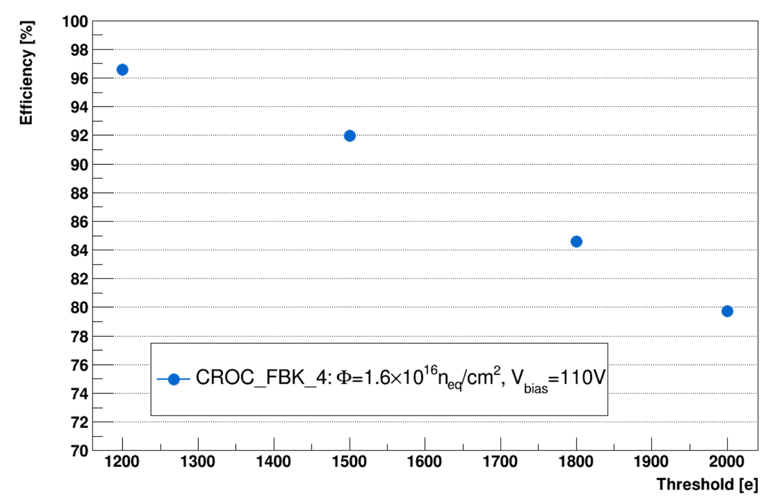
Hit resolution as a function of the track impact angle: a **minimum of 2 μm** is reached before irradiation. **Studies on irradiated sensors are ongoing.**



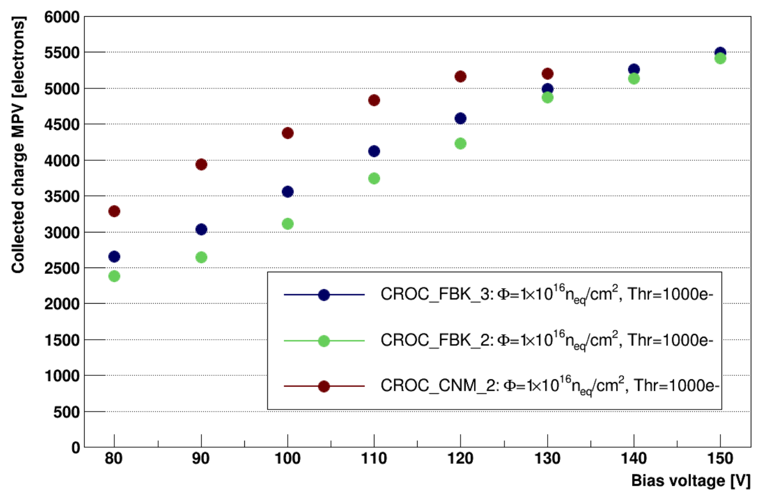
Hit detection efficiency as a function of the applied bias voltage at normal incidence. The **acceptance** is defined as **1 - (N_{masked}/N_{total})** and accounts for the stuck and noisy pixel. A fraction lower than 2% is tolerated after irradiation.



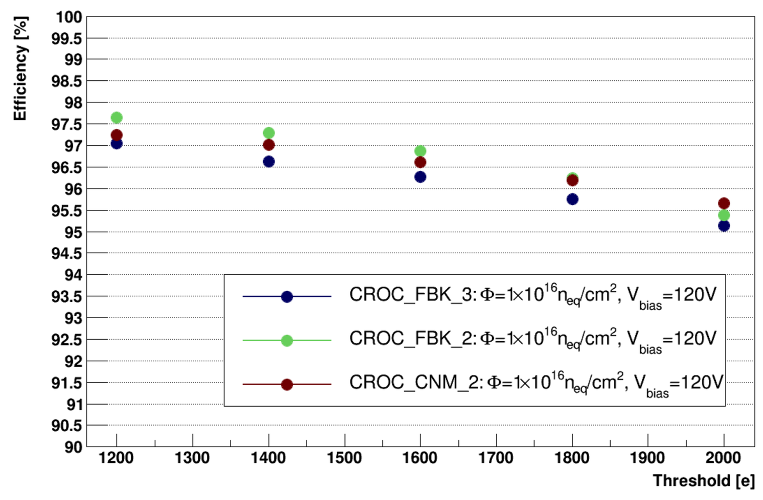
At higher irradiation fluencies (**1.6 x 10^{16} n_{eq}/cm²**) the efficiency plateau is reached for higher bias voltages —> **a detection efficiency larger than 96% at normal incidence is reached at 110 V meeting the specification requirements.**



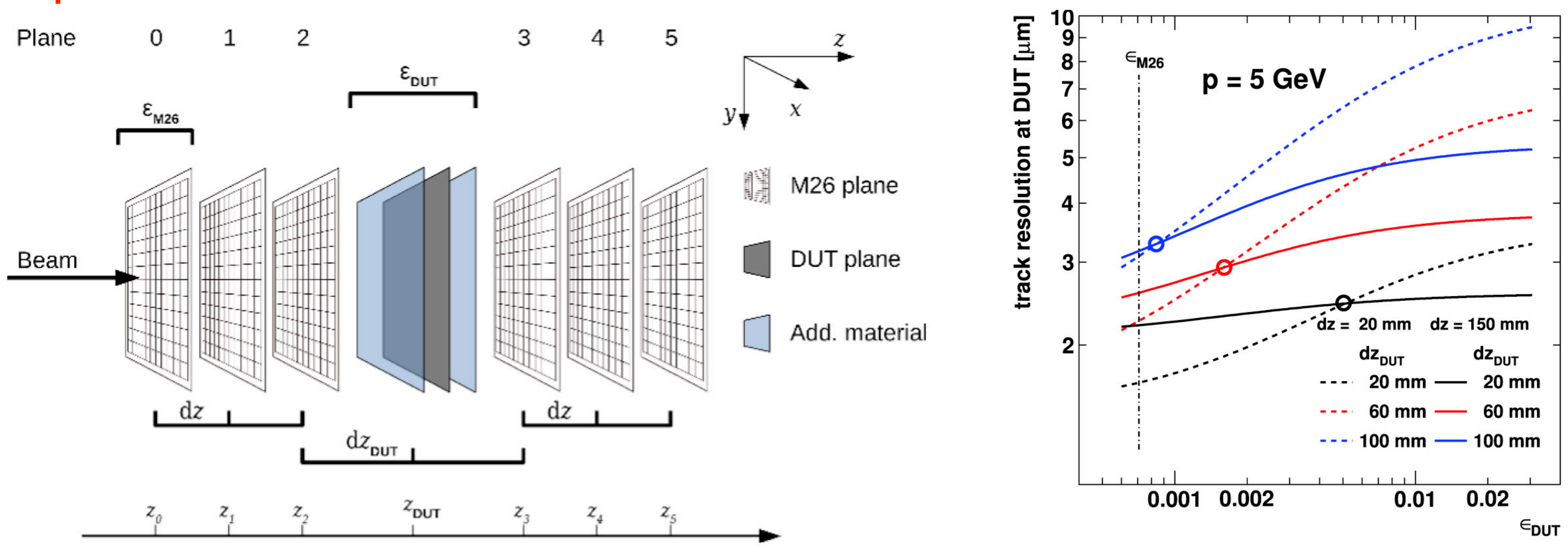
The impact of an increased threshold is larger when the sensors are more irradiated —> an increase of 300 electrons reduces the efficiency by 5%.



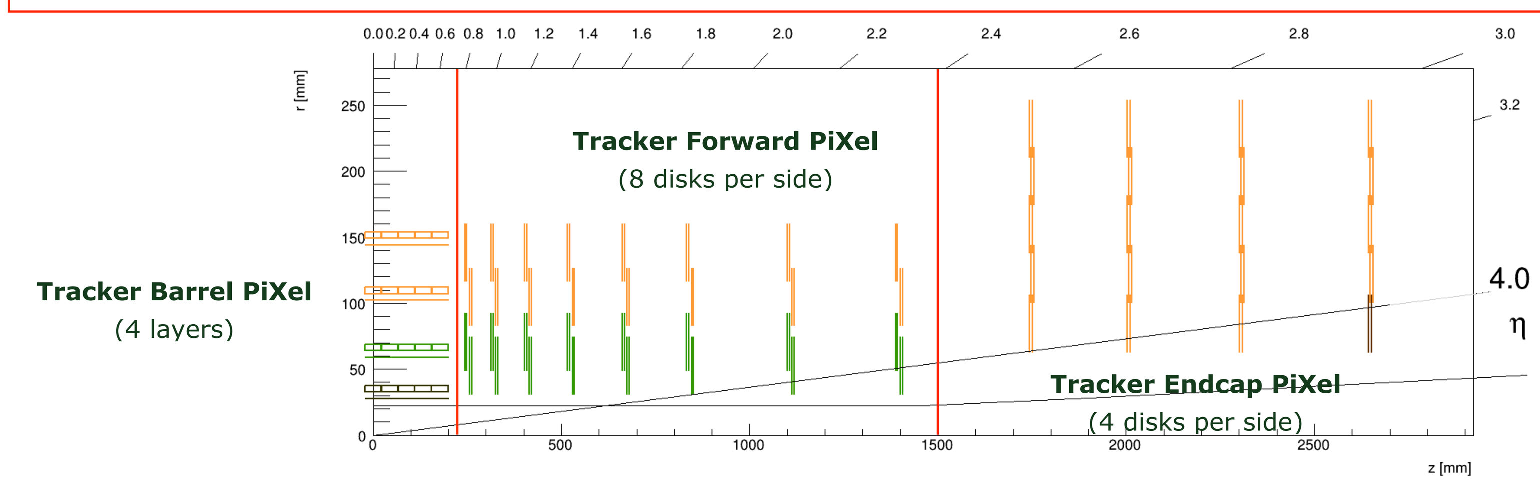
MPV of the collected charge as a function of the applied bias voltage. A reduction of a factor ~2 is observed after irradiation. Work is ongoing to estimate the impact on resolution.



Threshold scans are performed to investigate the performance at thresholds higher than the nominal one which might be required for operations in the final detector.



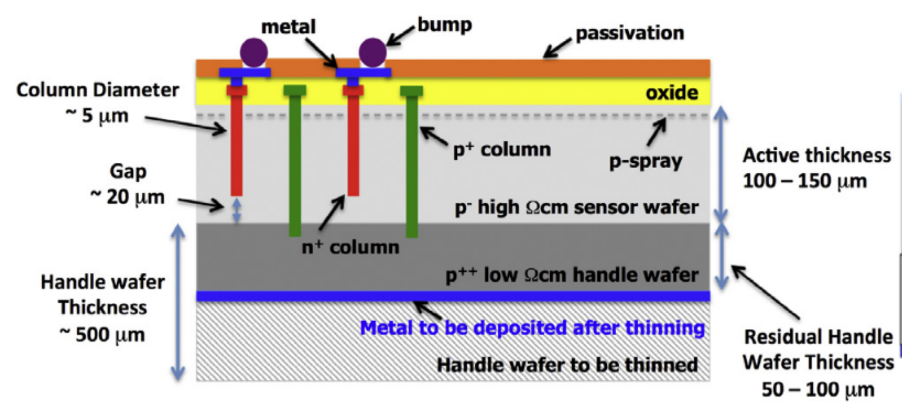
(a) Configuration (b) Resolution



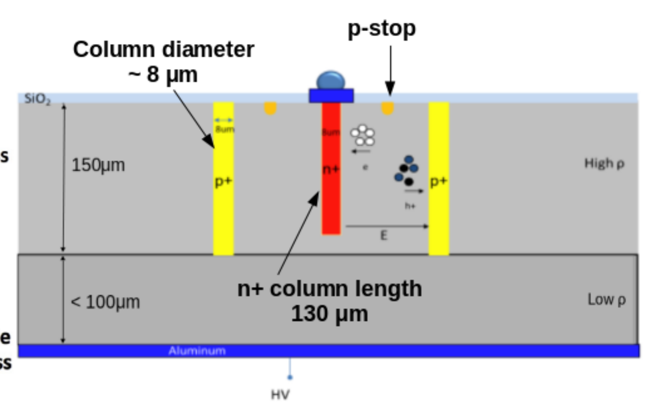
One quarter of the CMS Inner Tracker [1] detector: planar sensors will be assembled in **1 x 2 pixel modules** or **2 x 2 pixel modules** while 3D sensors will be assembled in **modules with 2 sensors and 2 ROCs**.
In order to improve vertex reconstruction the first layer of TBPX will be located closer to the beam pipe and the material budged will be reduced —> new mechanical structure required

- CMS R&D effort on 3D sensors in collaboration with Fondazione Bruno Kessler (FBK, Italy) and Centro Nacional de Microelectrónica (CNM, Spain).
- Floating zone **n+ on p type wafers**
  - collect electrons, fastest carriers
  - no type inversion of the bulk after irradiation
- Two p-type wafers bonded using **Direct Wafer Bonding** technique (developed by ICEMOS)
  - low resistivity layer —> mechanical support and ohmic contact
  - high resistivity layer —> active region of the sensor
- n+ and p+ columns etched on the same side —> cheaper than previous two sided process
- Production contract signed with FBK in June 2023 —> first order to be received in July 2024

Operation conditions	Sensor design constraints
Istantaneous luminosity up to 7.5 x 10^{34} cm⁻² s⁻¹, up to 200 events per 25 ns bunch crossing	Maintain occupancy at per mille level and increase the spatial resolution —> **pixel cell size** reduced from 100 x 150 μm² to **25 x 100 μm²**
Radiation level for first pixel layer after Run 4+5 (2200 fb⁻¹): 1.9 x 10^{16} n_{eq}/cm² —> carriers lifetime ~ 0.3 ns, mean free path ~ 30 μm for electrons at saturation velocity	Reduce distance between electrodes to increase the signal —> **thin planar or 3D columnar** technologies
150 μm thick planar sensors are baseline for the CMS Inner Tracker (see the poster by Bianca Raciti) 3D sensors will be employed in TBPX Layer 1 due to their lower power dissipation See the poster by Michael Grippo for more details on the readout chip (ROC)	



FBK 3D sensor sketch



CNM 3D sensor sketch

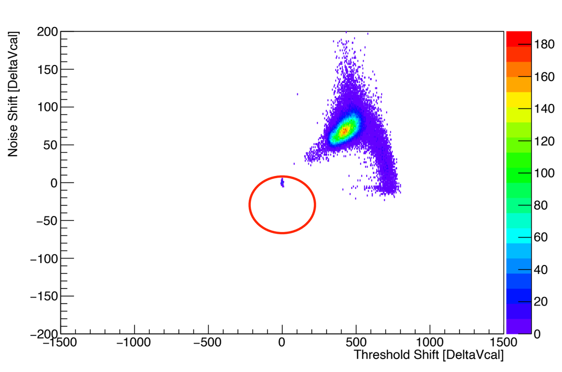
"**Hybridisation**" is the name given to the process of assembling sensors and ROCs into modules.

INFN Firenze team assembled 6 double modules using 3D single chip modules produced by Advafab

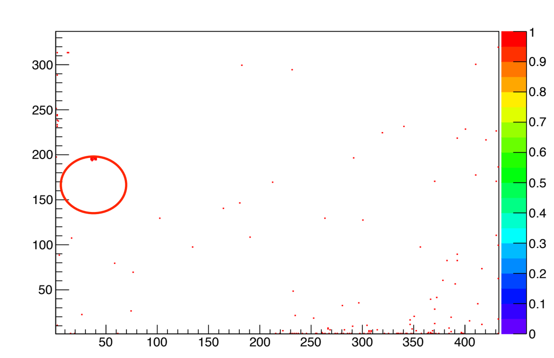
Bump bonding quality assessed using two methods:

- **Exposure to X-rays or beta-sources**: limited by the availability of instruments but easy selection to identify disconnected bumps (pixel occupancy < threshold —> disconnected bump)
- "**Forward bias**":
  - **Compare threshold and noise distributions** obtained for a high threshold value (e.g. 6000 electrons) applying a **reverse bias voltage (-5 V) and small forward bias voltage (+ 0.5 V)**
  - Threshold and noise of sensor pixels properly bump bonded to the ROC are expected to shift while **disconnected ones will show the same values**.
  - Do not require additional instrumentation
  - Selection on the threshold and noise shifts to be uniformly employed in all the production centres

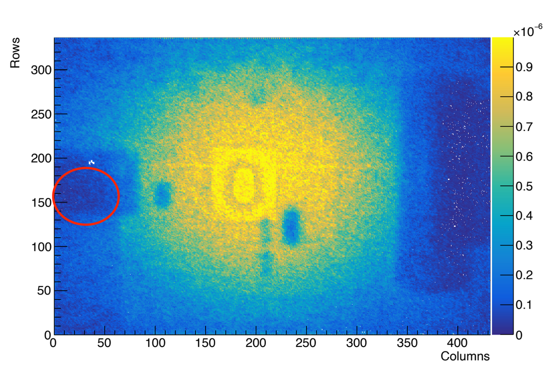
Threshold for quality control: < 600 disconnected bumps per chip



2D map of the noise and threshold shifts for a chip belonging to a double 3D module: a group of disconnected bumps is identified near (0,0)



The rows and columns of the disconnected bumps are extracted and a 2D map is filled for better visualisation

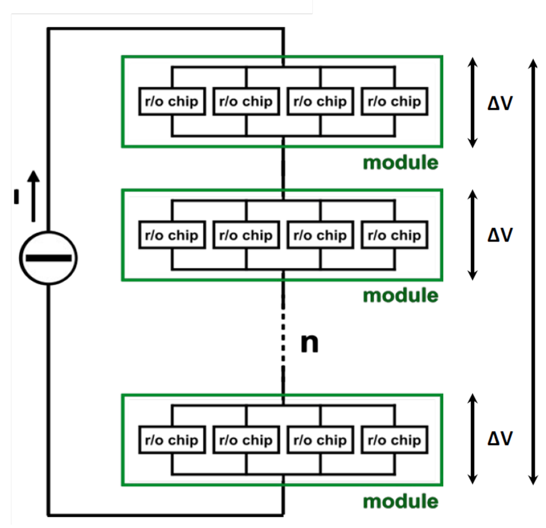


Pixel occupancy from resulting from exposure of the same module to a beta source —> same disconnected pixels are identified

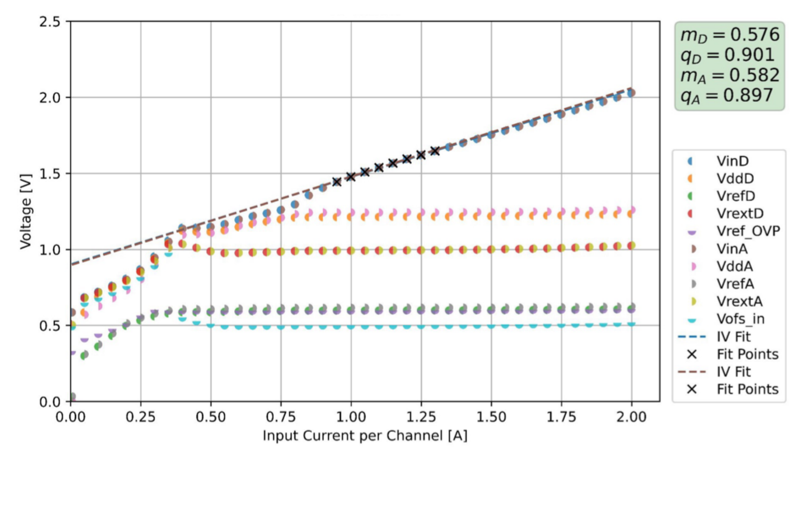
The powering scheme of the modules in the current CMS pixel detector could not be ported to the design of the upgraded CMS Inner Tracker because of the limited radiation tolerance of the DC-DC converters.

Modules in the CMS IT will be connected in "**serial powering**" chains composed by 8 to 11 modules. ROCs in each module will be connected in parallel. This scheme will be implemented through special regulators named Shunt-LDO (Low DropOut) [2].

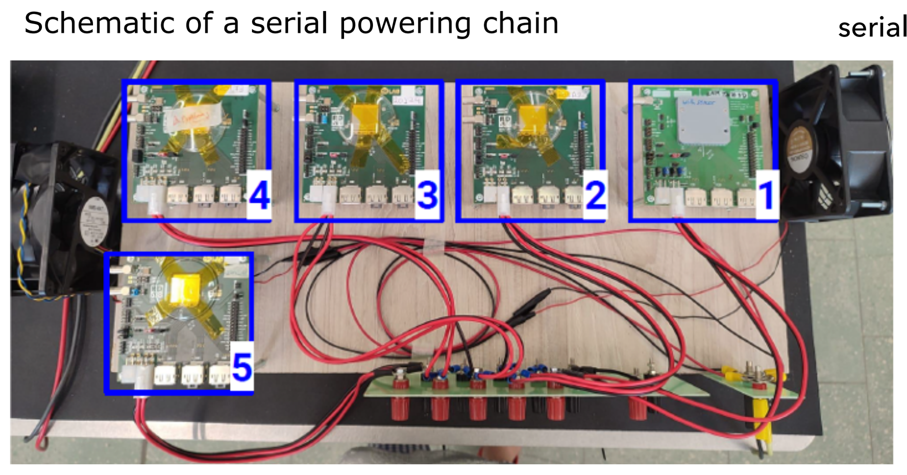
The regulator provides the correct voltage (1.2 V) to the analog and digital domains of the ROC while the shunt dumps the current not consumed by the domain (current consumption is variable!) and provides a safety mechanism against single failures in the chain.

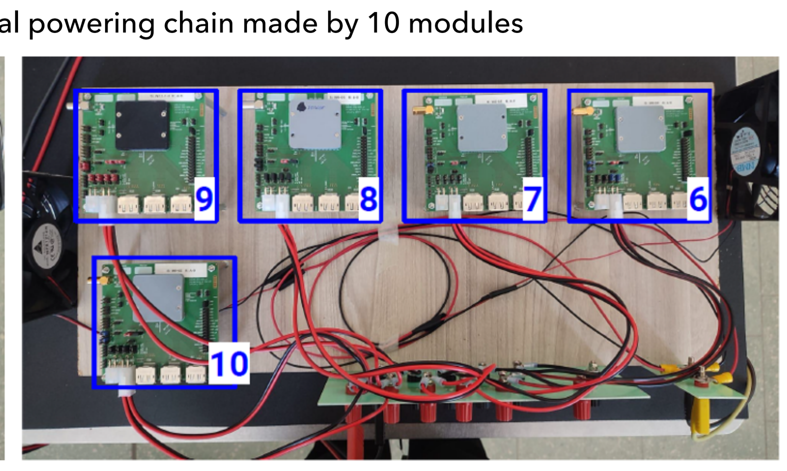


Schematic of a serial powering chain



V – I curve of a 3D single chip assembly inserted in a serial powering chain made by 10 modules





[1] "The Phase-2 Upgrade of the CMS Tracker" - https://cds.cern.ch/record/2272264
[2] "An integrated Shunt-LDO regulator for serial powered systems" - https://doi.org/10.1109/ESSCIRC.2009.5325974