The CMS Pixel Detector for the High Luminosity LHC

Giacomo Sguazzoni
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Sezione di Firenze

on behalf of the CMS Tracker Group

VERTEX2022: the 31st International Workshop on Vertex Detectors

Inner Tracker (IT)

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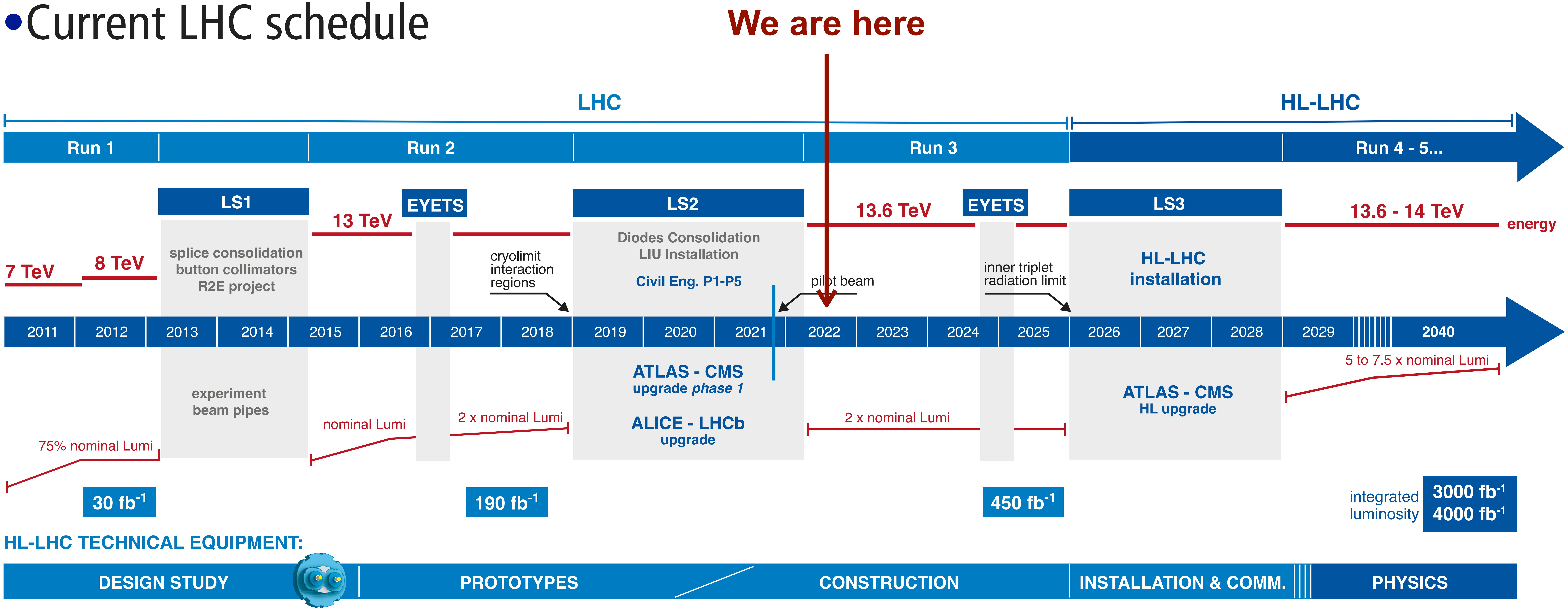
Where do we stand?

- Current LHC schedule

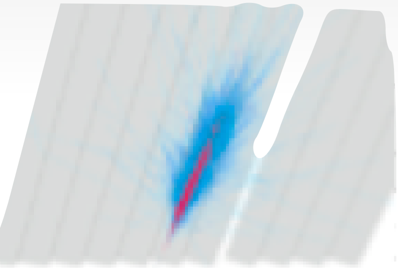


The CMS detector

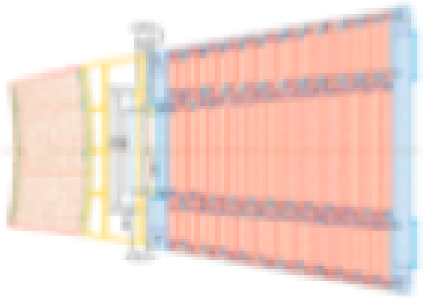
Superconducting Coil, 4 Tesla

CALORIMETERS

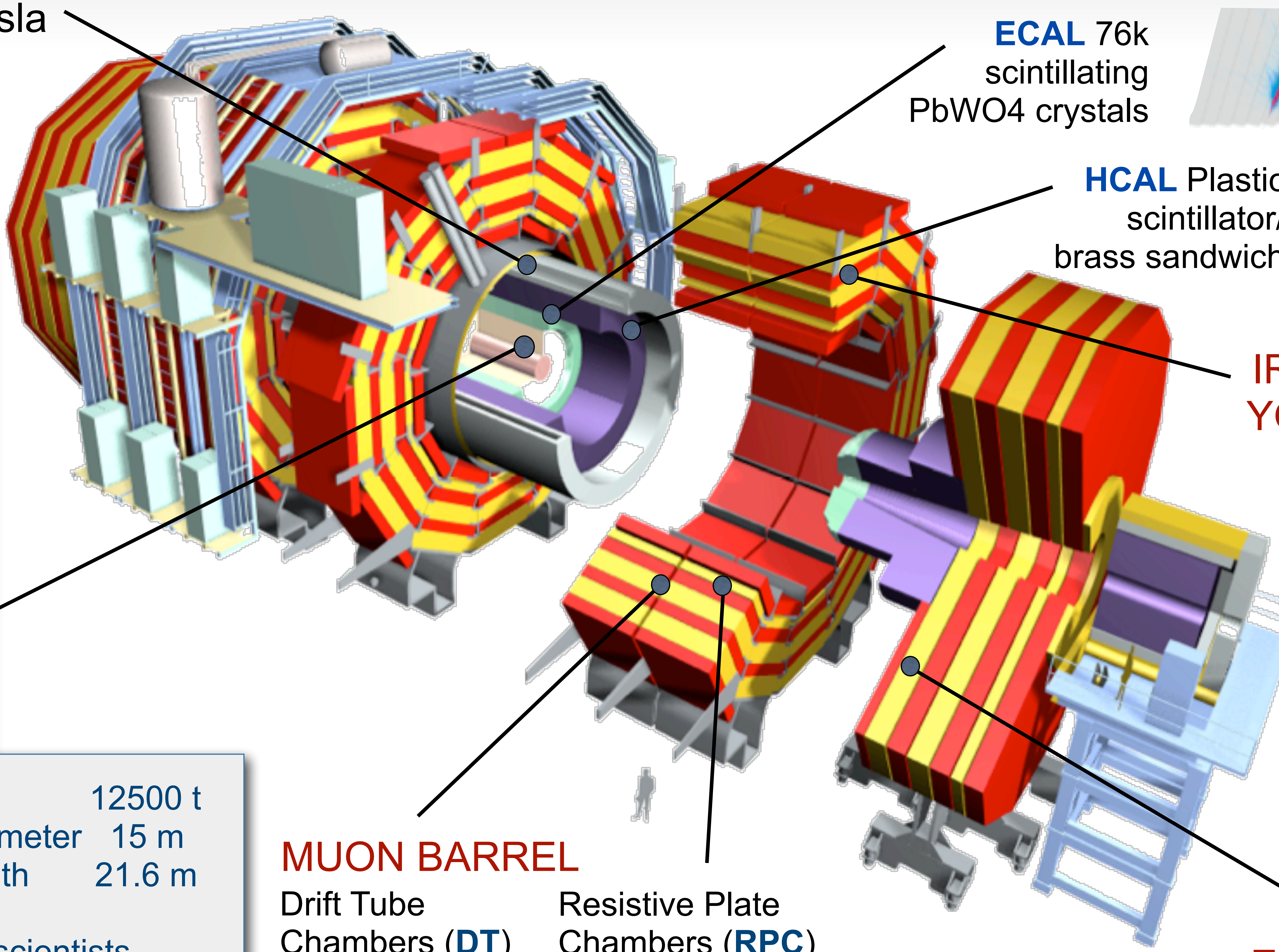
ECAL 76k scintillating PbWO4 crystals

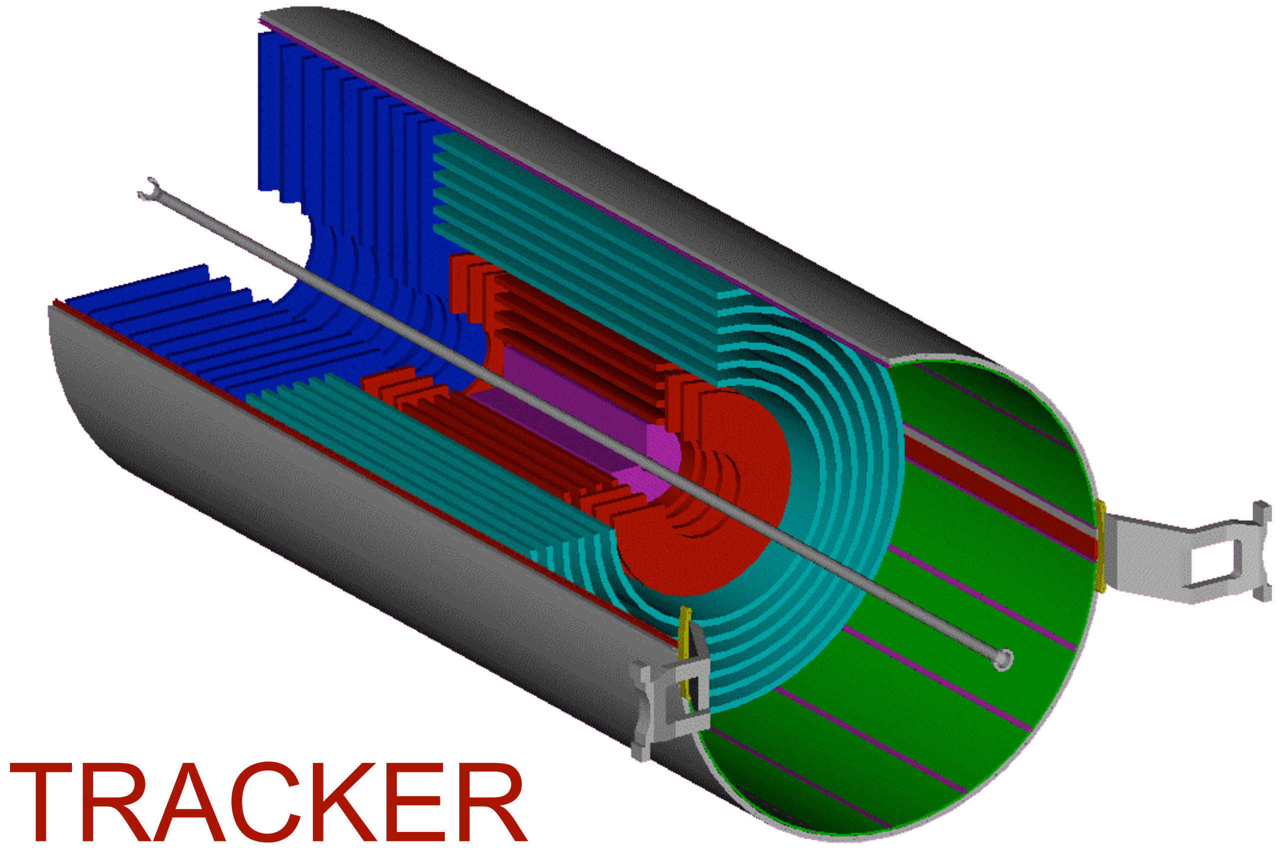


HCAL Plastic scintillator/ brass sandwich



IRON YOKE





TRACKER

~1.8m² 100x150μm² Si-pixels

~200m² Si μ-strips

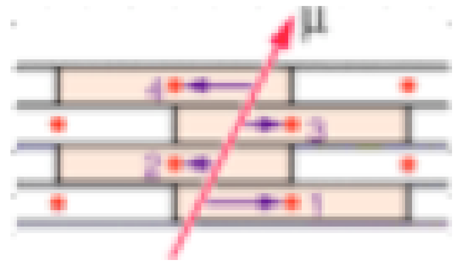
~130M channels

Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

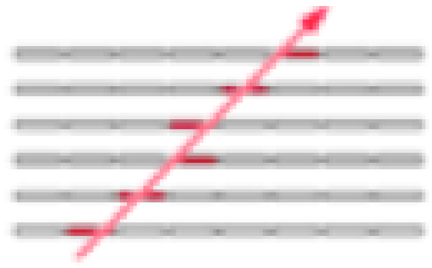
~3400 scientists
245 institutes
57 countries

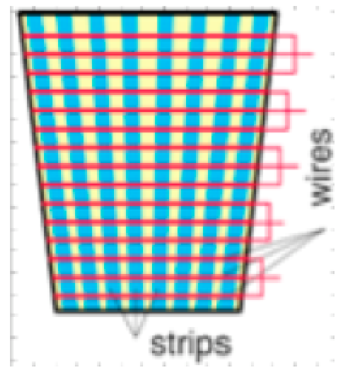
MUON BARREL

Drift Tube Chambers (**DT**)



Resistive Plate Chambers (**RPC**)





MUON ENDCAPS

Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

The High Luminosity phase of LHC (phase-2)

LHC experiments will undergo substantial upgrades to be ready for phase-2 in 2028; the CMS Tracker needs to be completely replaced because it will underperform in the harsh HL-LHC conditions and will not survive radiation…

LHC 2010-2025	**HL-LHC** 2030-2040
7-14TeV	14 TeV
$L_{IST} = \mathbf{2 \cdot 10^{34} cm^{-2} s^{-1}}$	$L_{IST} = \mathbf{5\text{-}7.5 \cdot 10^{34} cm^{-2} s^{-1}}$
PU<**50-60**	PU=**140-200**
$L_{INT} = \mathbf{450 fb^{-1}}$	$L_{INT} = \mathbf{3000\text{-}4000 fb^{-1}}$

Now!

from 2030 on!

PU mitigation

High rate capability

Radiation hardness

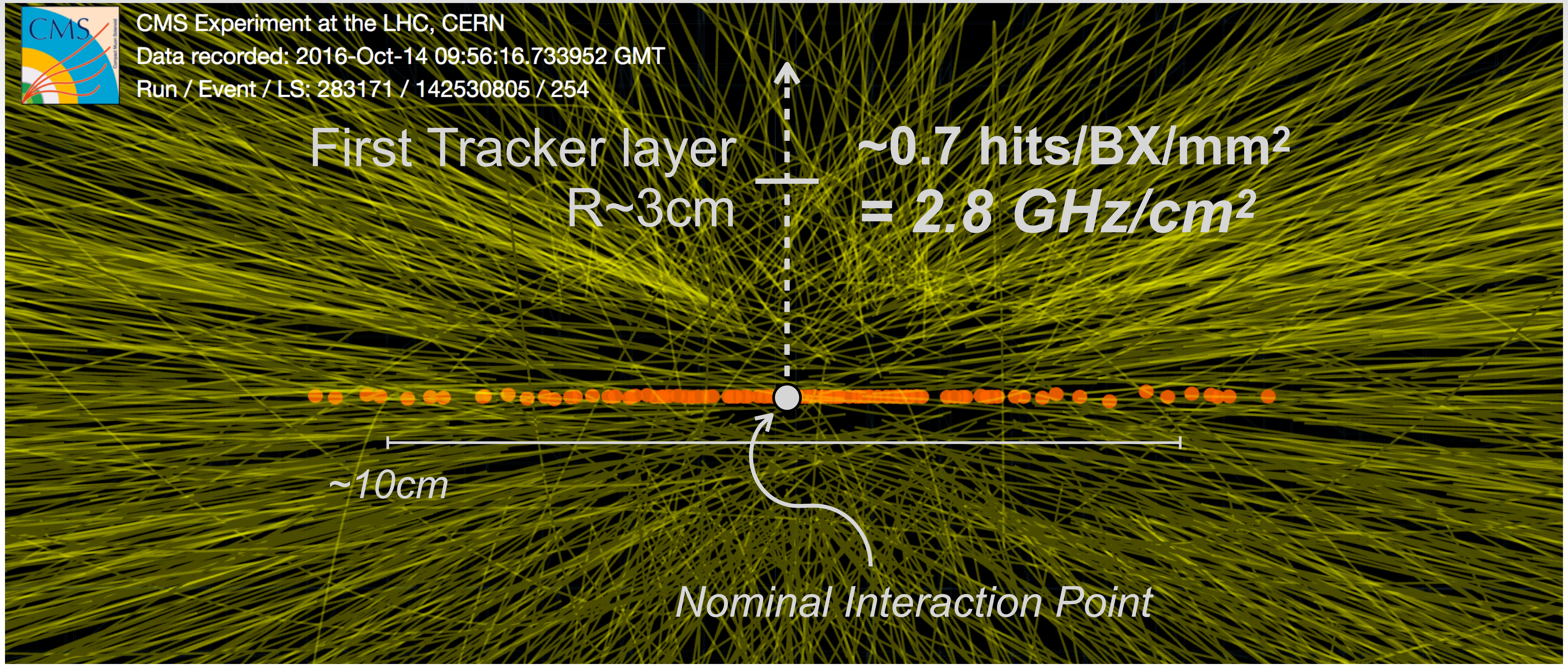
Upgrades

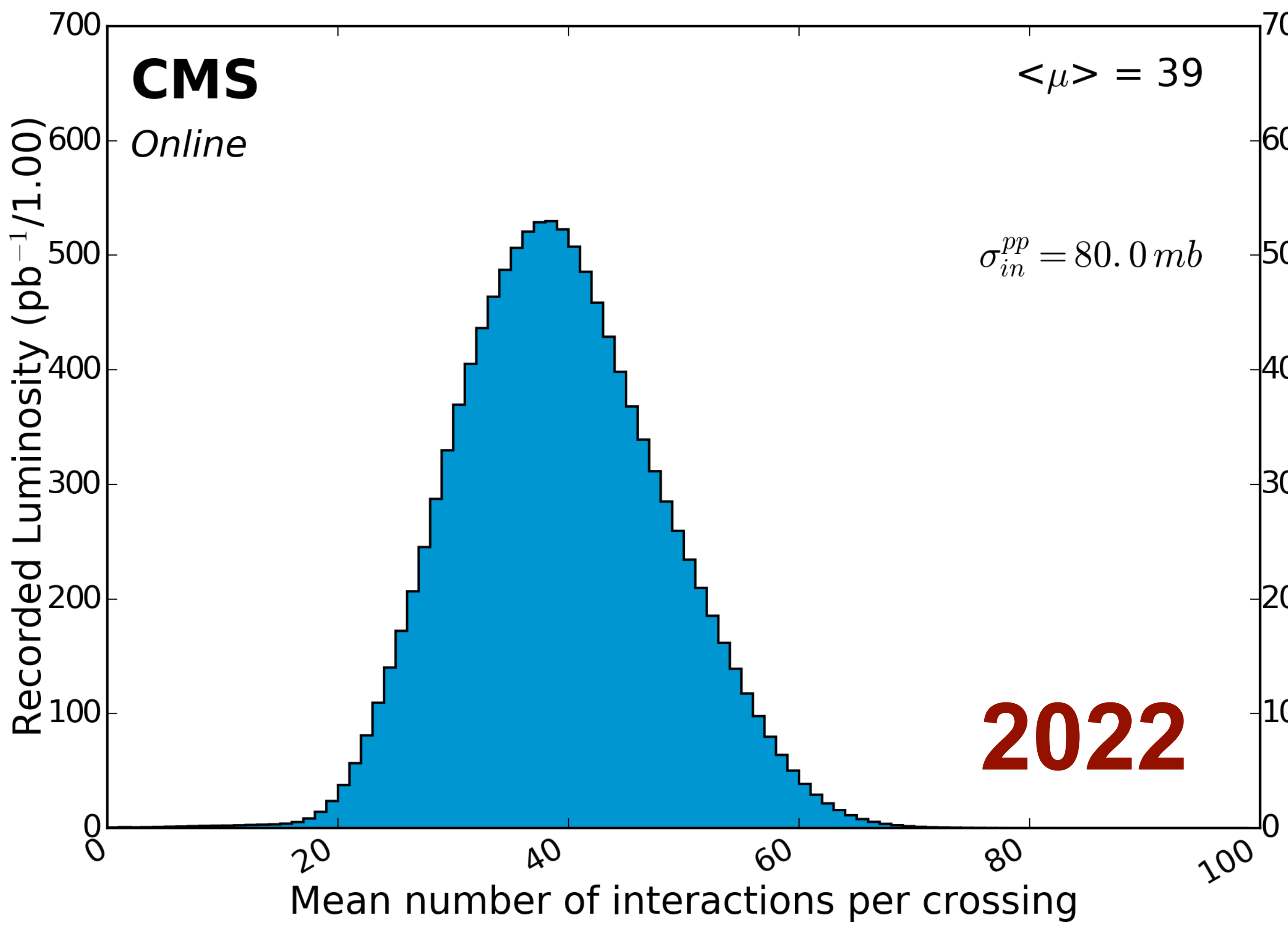
Reduced material

Trigger strategies

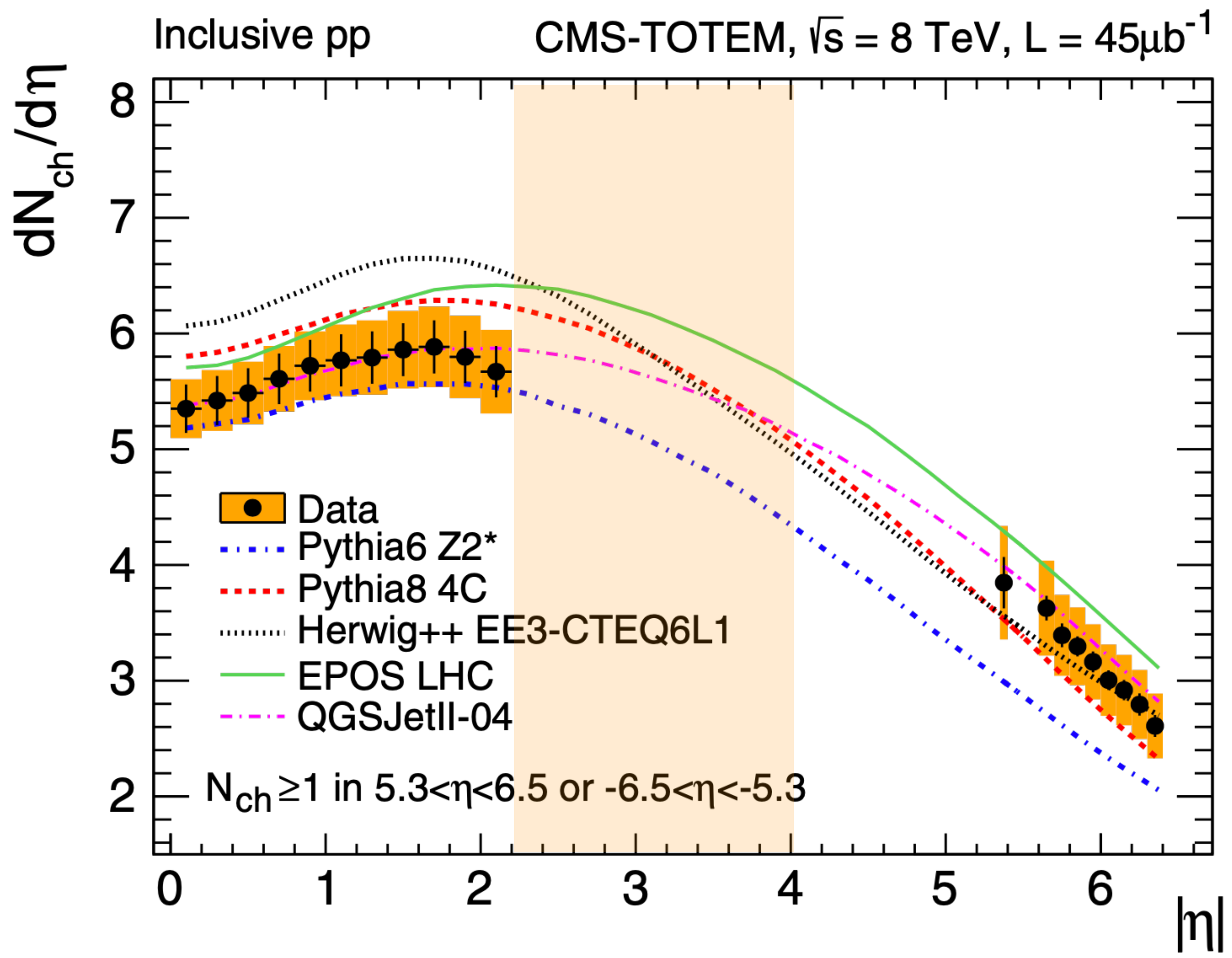
N.A. for the Inner Tracker

PU and Rates





PU distribution in 2022 data (source)

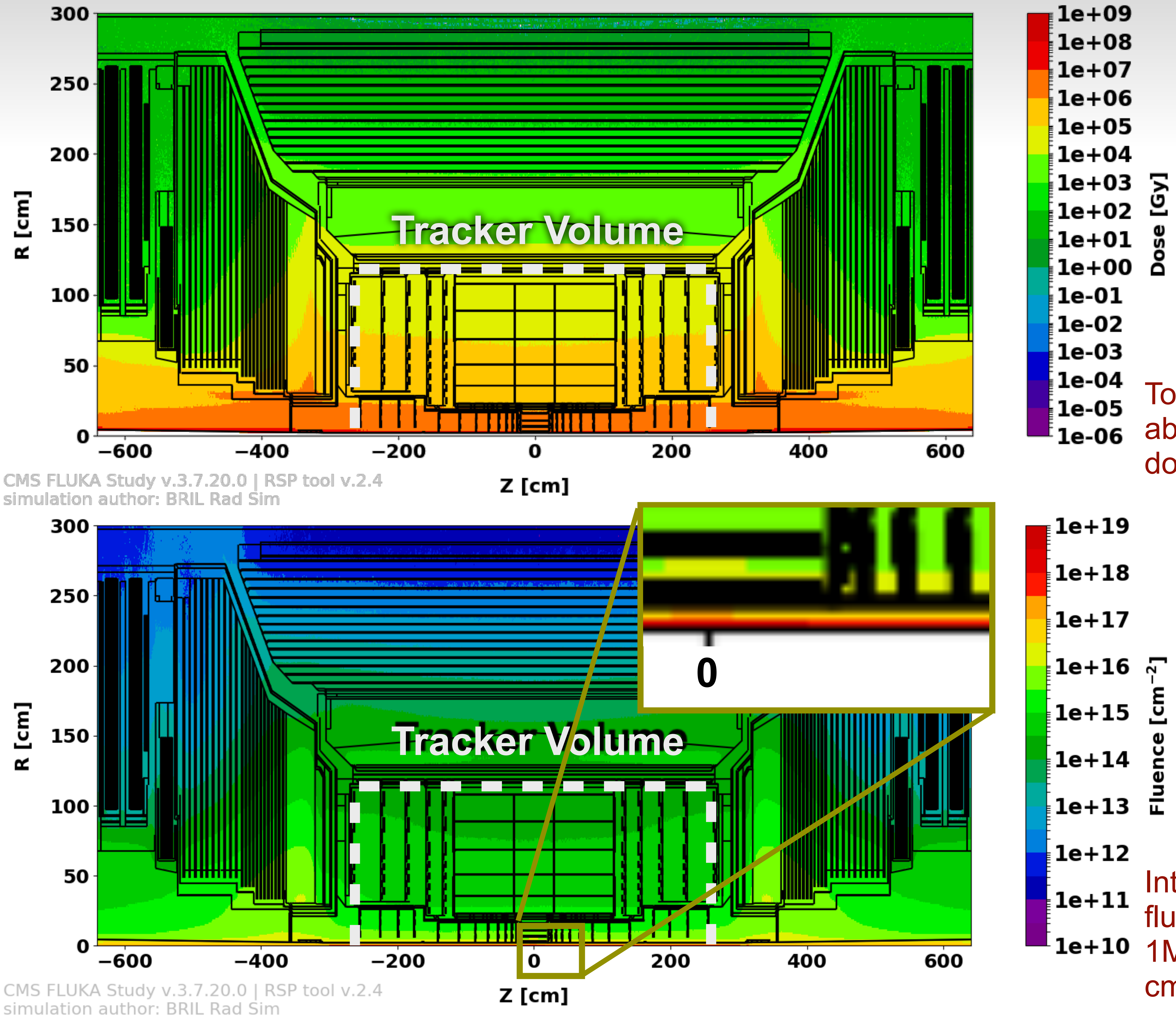


Charged track distribution vs. |eta| in 8TeV pp events (source)

Radiation environment

At the first active layer (~3cm from the beam line):

- dose well exceeding the Grad;
- fluence up to several 10^{16}neq/cm^2



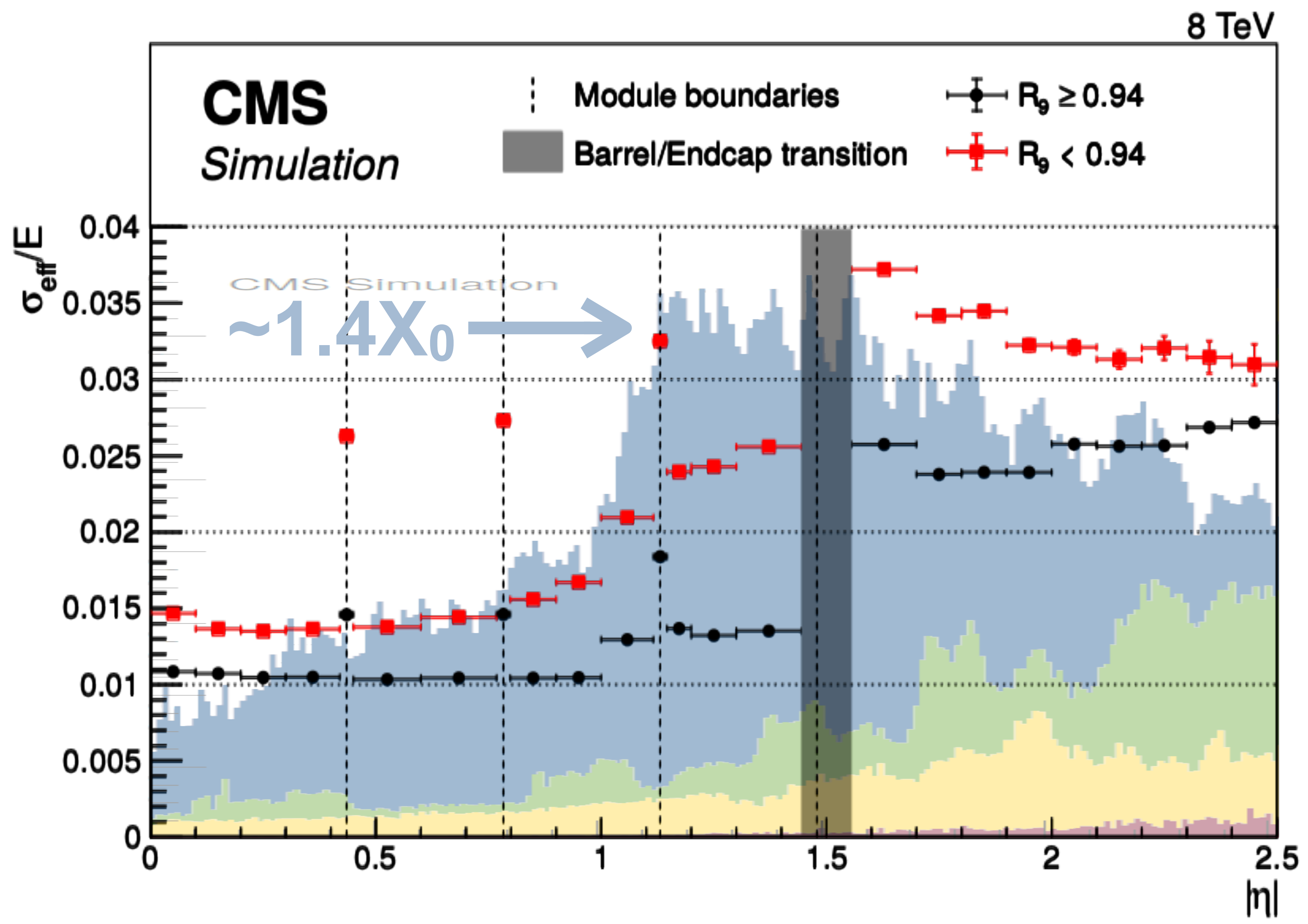
Total absorbed dose in Gray

Integrated fluence in 1MeV neq/cm^2

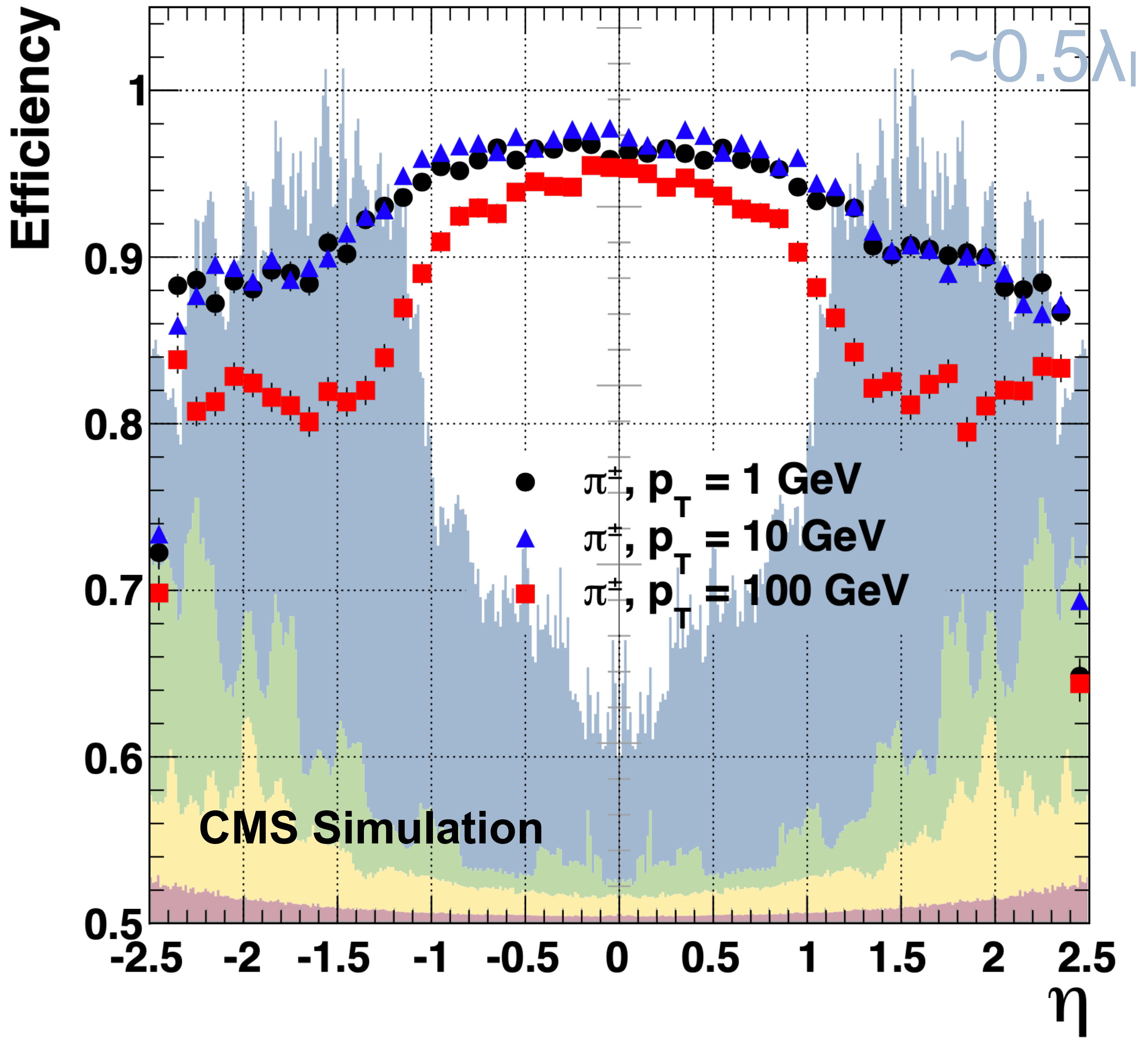
The hidden upgrade

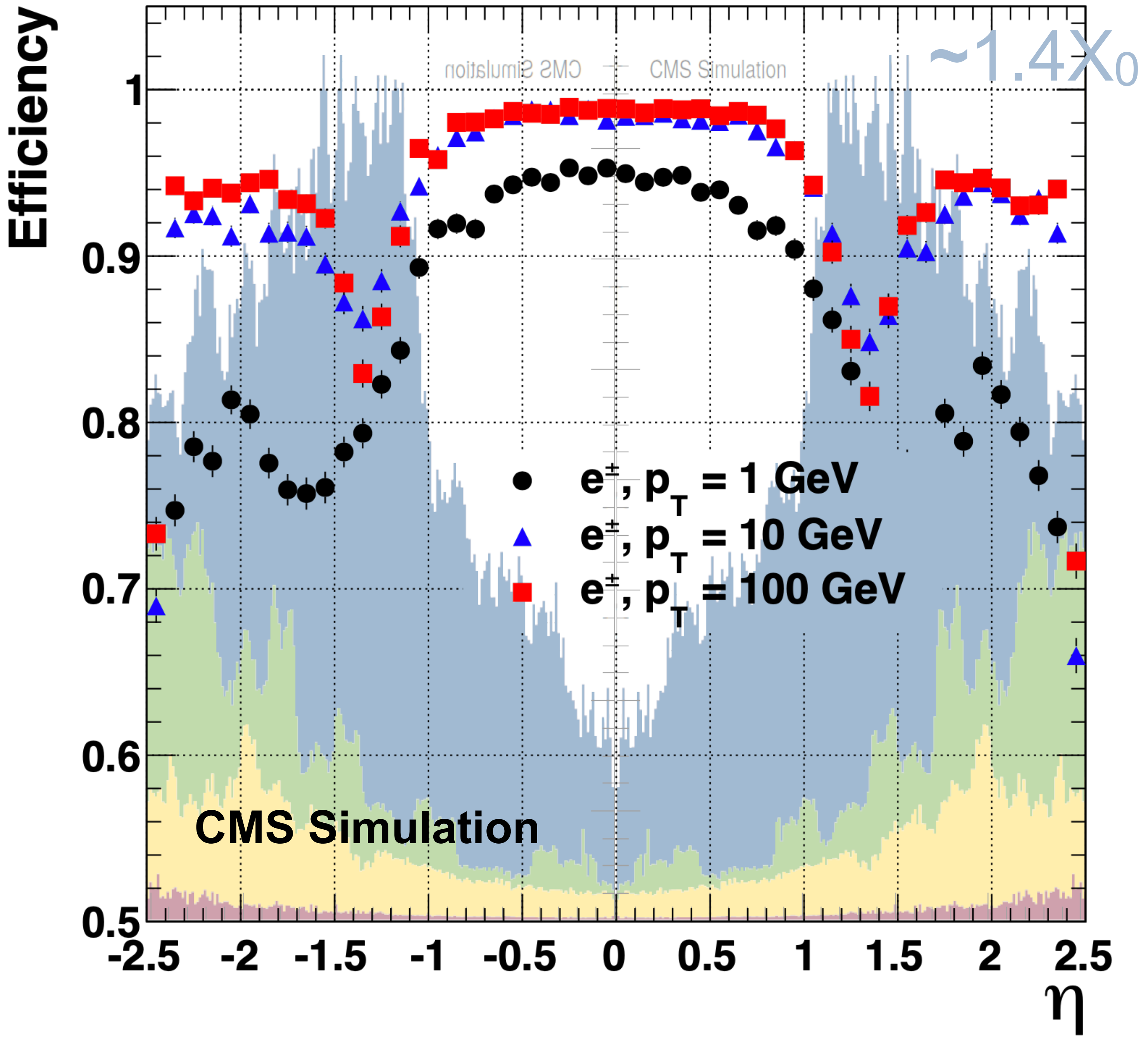
current detector

Passive material is one of the current tracker main limitations; it is dangerous for tracking and downstream detectors. Degradation in tracking (vertexing, impact parameter, momentum resolution, pattern recognition) and in electromagnetic calorimeter performance. **The Tracker Upgrade project is committed to minimize the passive material!**



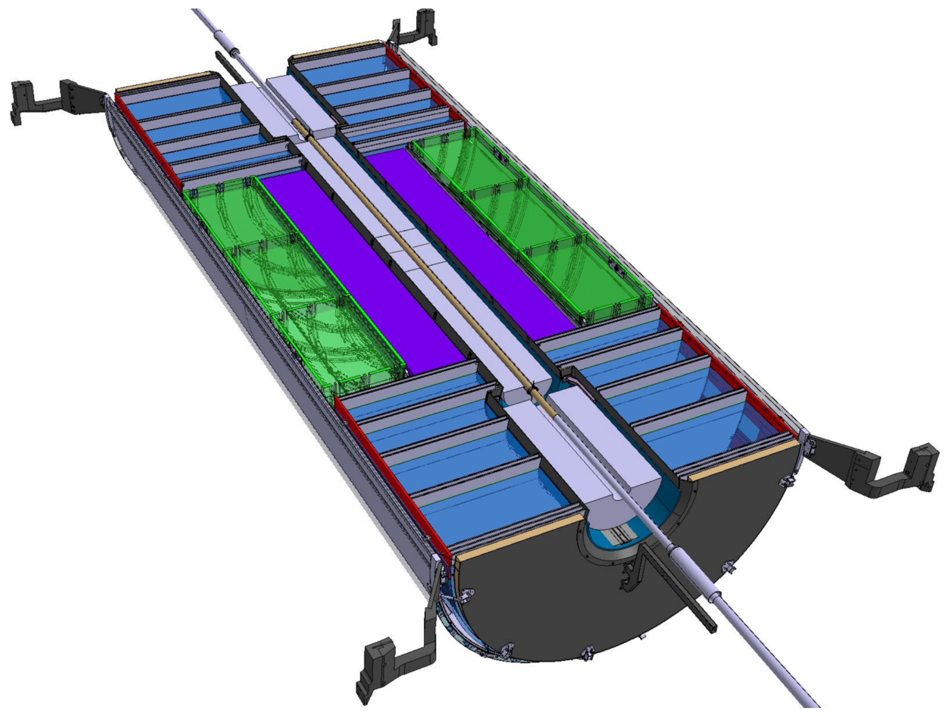
ECAL energy resolution in H→γγ events for **converted** (**not converted**) photons in the upstream (tracker) material (source); the tracker material profile (X_0) is superimposed.



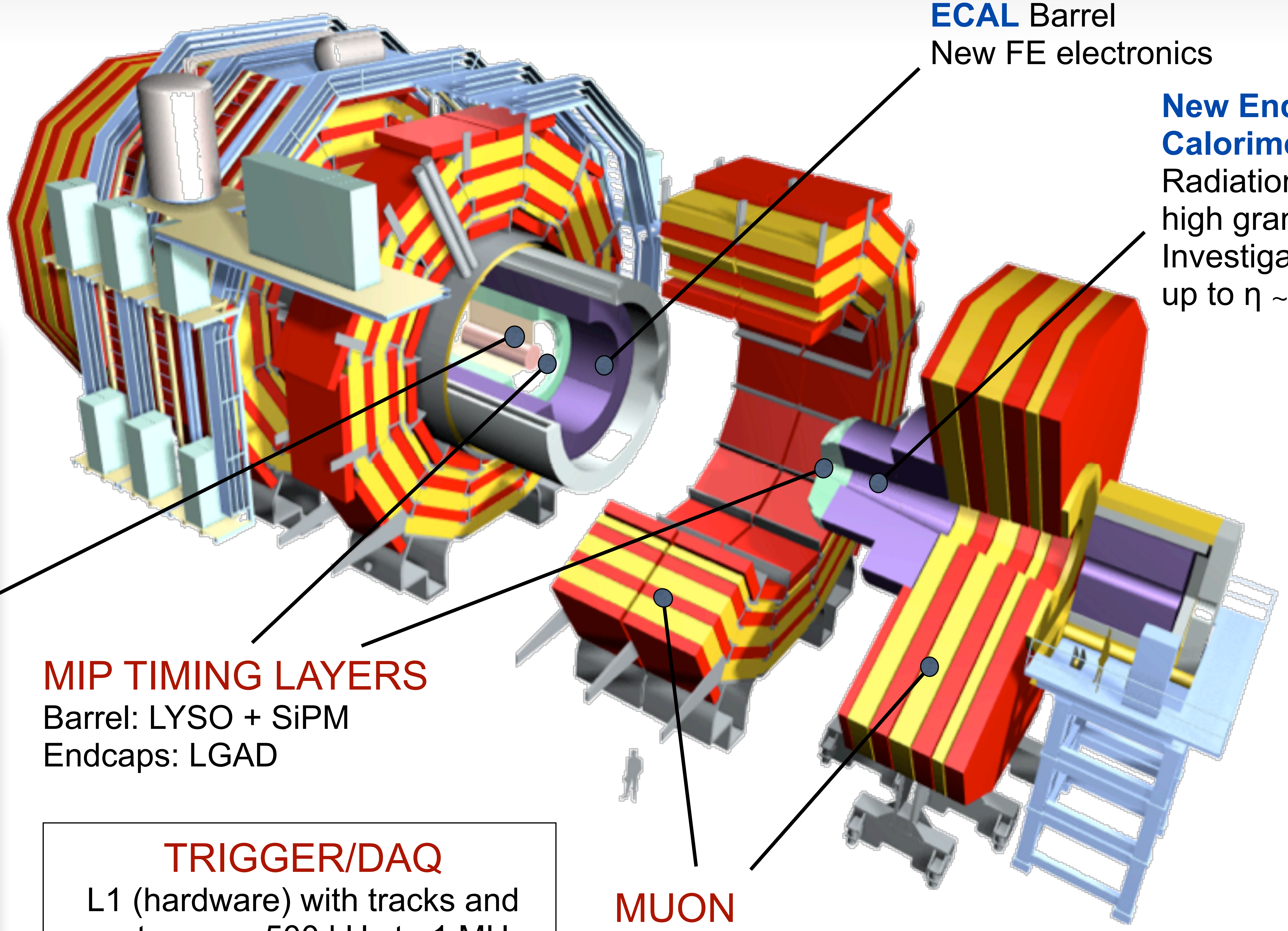


Track reconstruction efficiencies for pions (left) and electrons (right) as a function of η (left), for p_T = 1, 10, and 100 GeV (source).
The tracker material profile (in λ_I and X_0 respectively) is superimposed.

The phase-2 upgrade



NEW TRACKER
Radiation tolerant - high granularity - less material
Tracks in L1 trigger
Coverage up to η ~ 4



CALORIMETERS
ECAL Barrel
New FE electronics

New Endcap Calorimeters
Radiation tolerant - high granularity
Investigate coverage up to η ~ 4

MIP TIMING LAYERS
Barrel: LYSO + SiPM
Endcaps: LGAD

TRIGGER/DAQ
L1 (hardware) with tracks and rate up ~ 500 kHz to 1 MHz
Latency ≥ 10 μs
HLT output up to 10 kHz

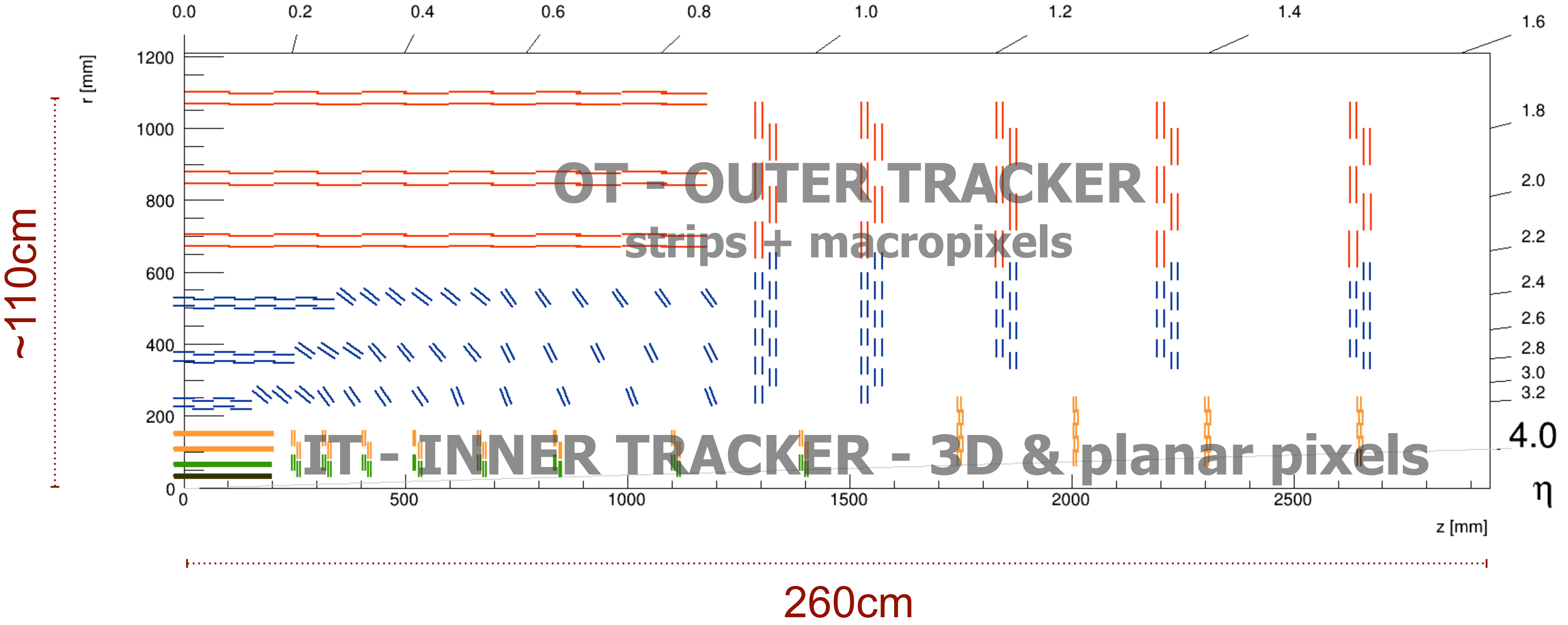
MUON
Replace DT FE electronics
Complete RPC coverage in forward region (new GEM/RPC technology)

CMS (Inner) Tracker upgrade requirements

The Outer Tracker and the Inner Tracker are part of the same project. Some requirements do apply only on the IT and viceversa

- **Radiation tolerance and cold (–20°C) operation to be functional up to 3ab^{-1} (with margins to comply with the best performance scenario)**
- **Optimized layout and granularity for robust pattern recognition in 140-200PU environment** (occupancy <O(1%) for the OT and **<O(0.1%) for the IT**)
- **Reduced passive material with respect to phase-1 tracker**
- ~~Track Trigger capabilities to contribute to L1~~ (only OT) **N.A. for the Inner Tracker**
- **Large readout bandwidth and deep front-end buffers compliant with the rate (750kHz) and the long latency (12.5μs) of the upgraded L1 trigger system**
- **Coverage up to |η|~4 for efficient PU mitigation and better physics objects reconstruction in the forward region**
- Extra requirements:
  - **very forward part of IT usable as a luminosity monitor**
  - **IT fully accessible for maintenance and part replacement**

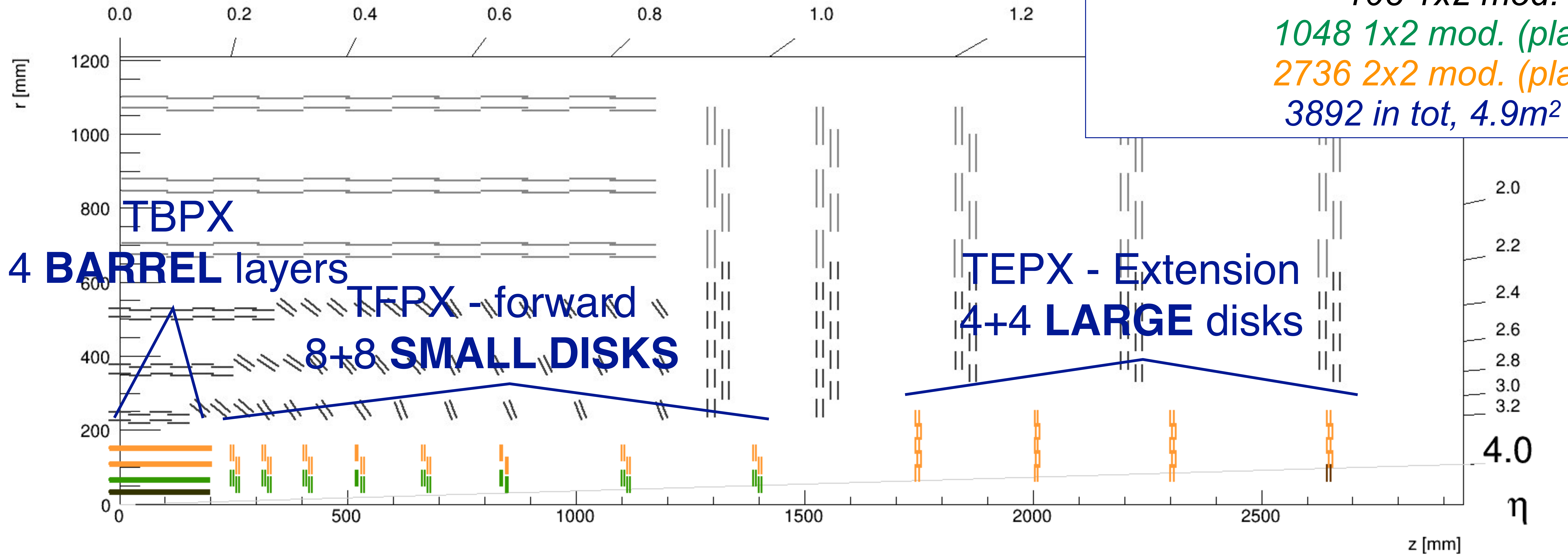
The new tracker layout

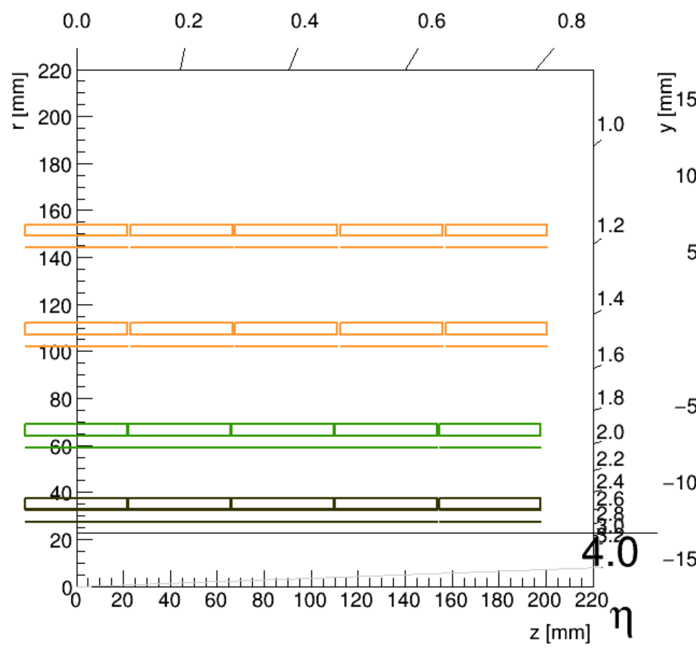
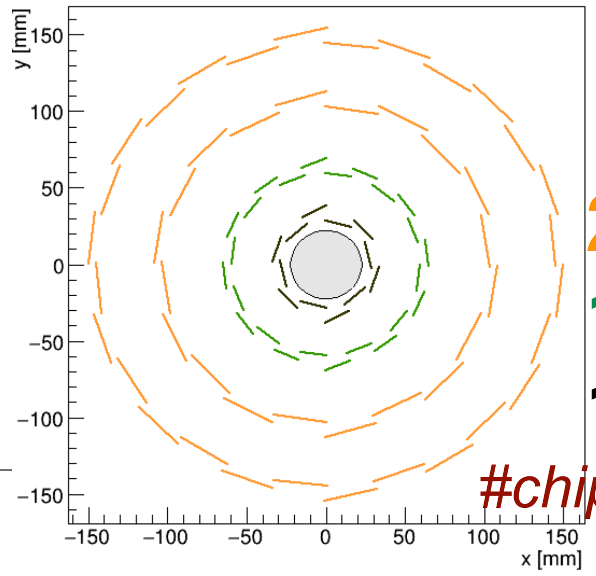


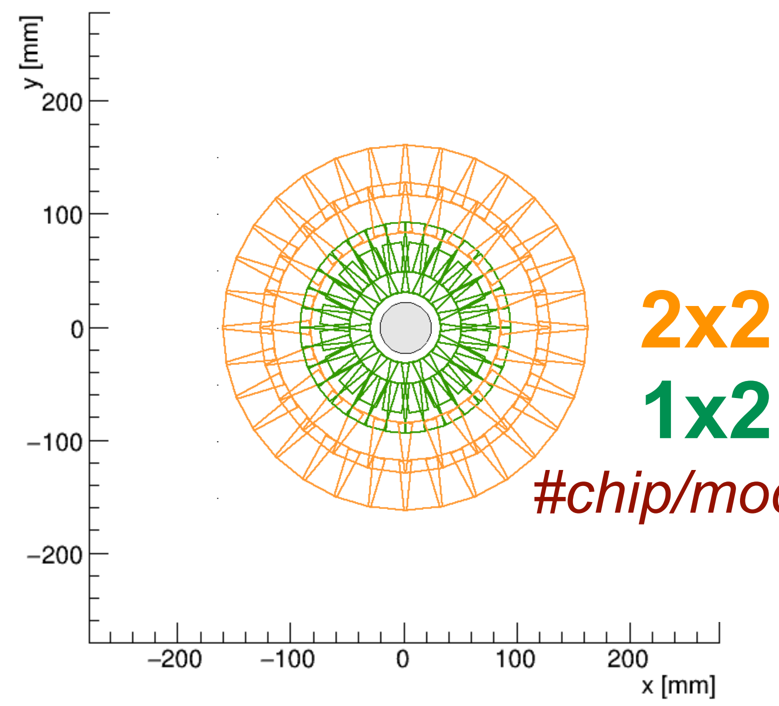
OT800_IT702

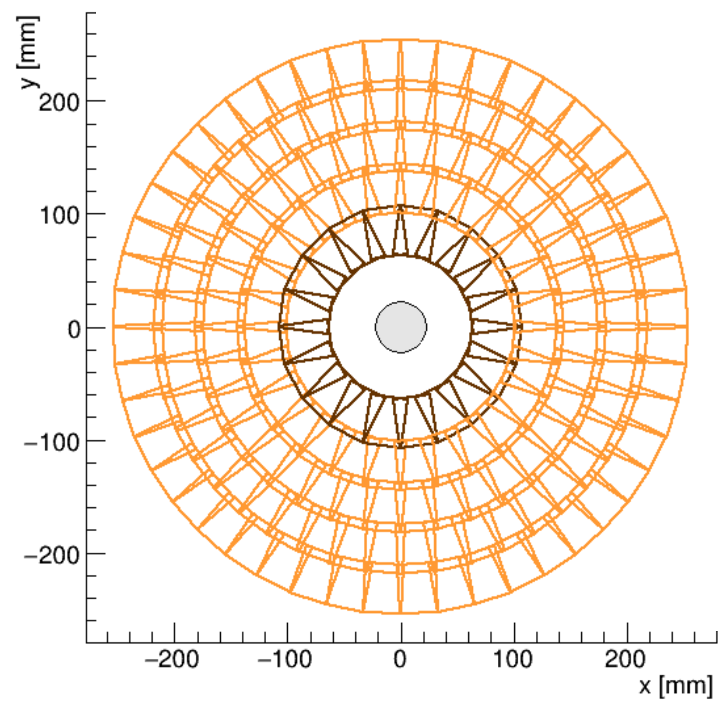
The new tracker layout - Inner Tracker

108 1x2 mod. (3D)
1048 1x2 mod. (planar)
2736 2x2 mod. (planar)
3892 in tot, 4.9m² of Si

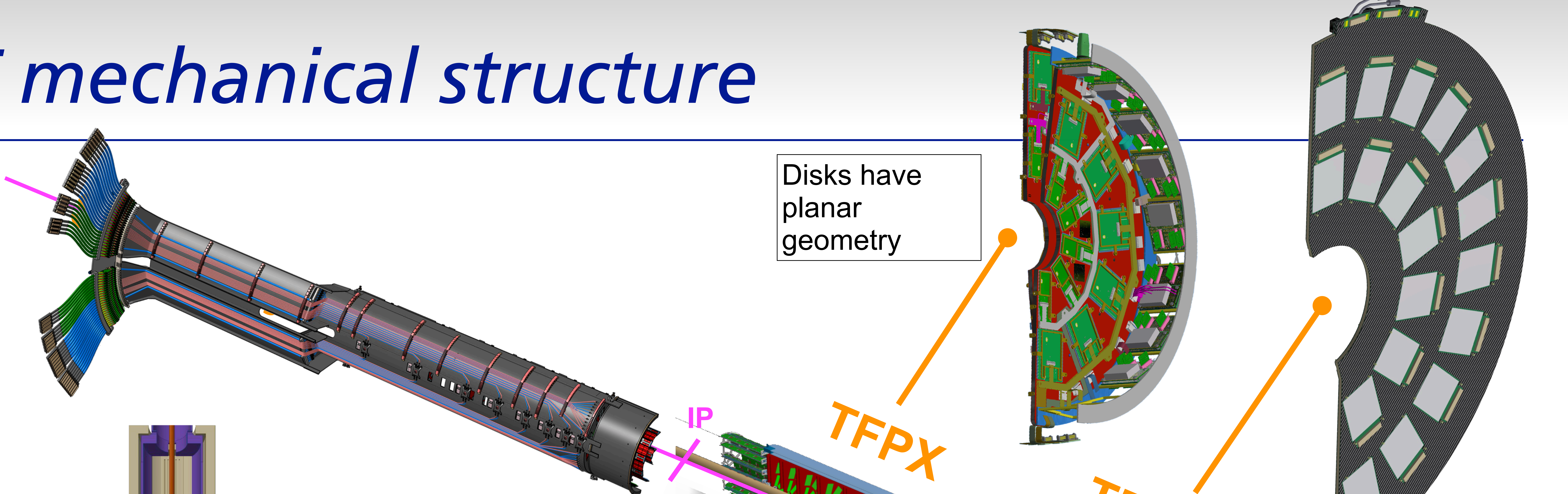


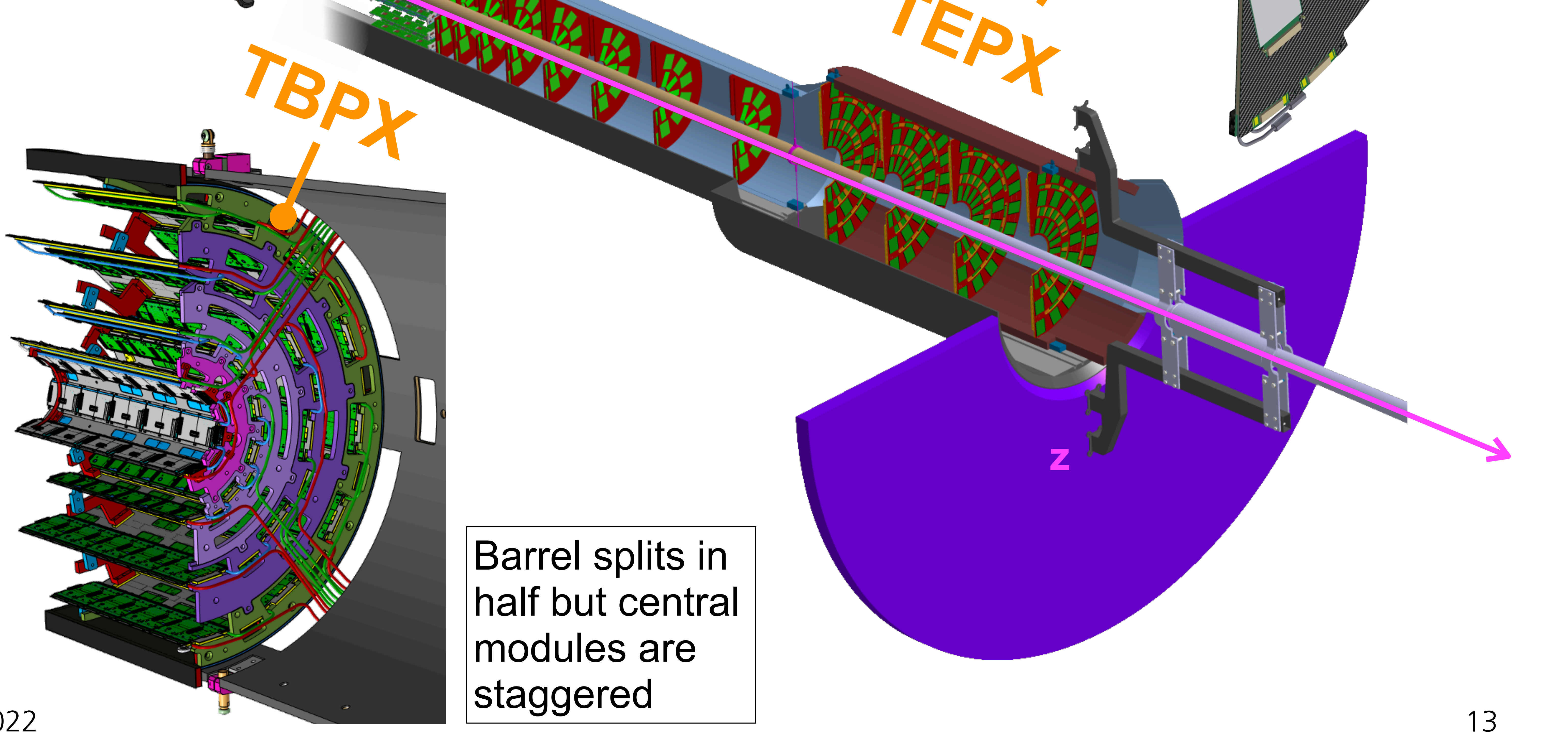







The IT mechanical structure

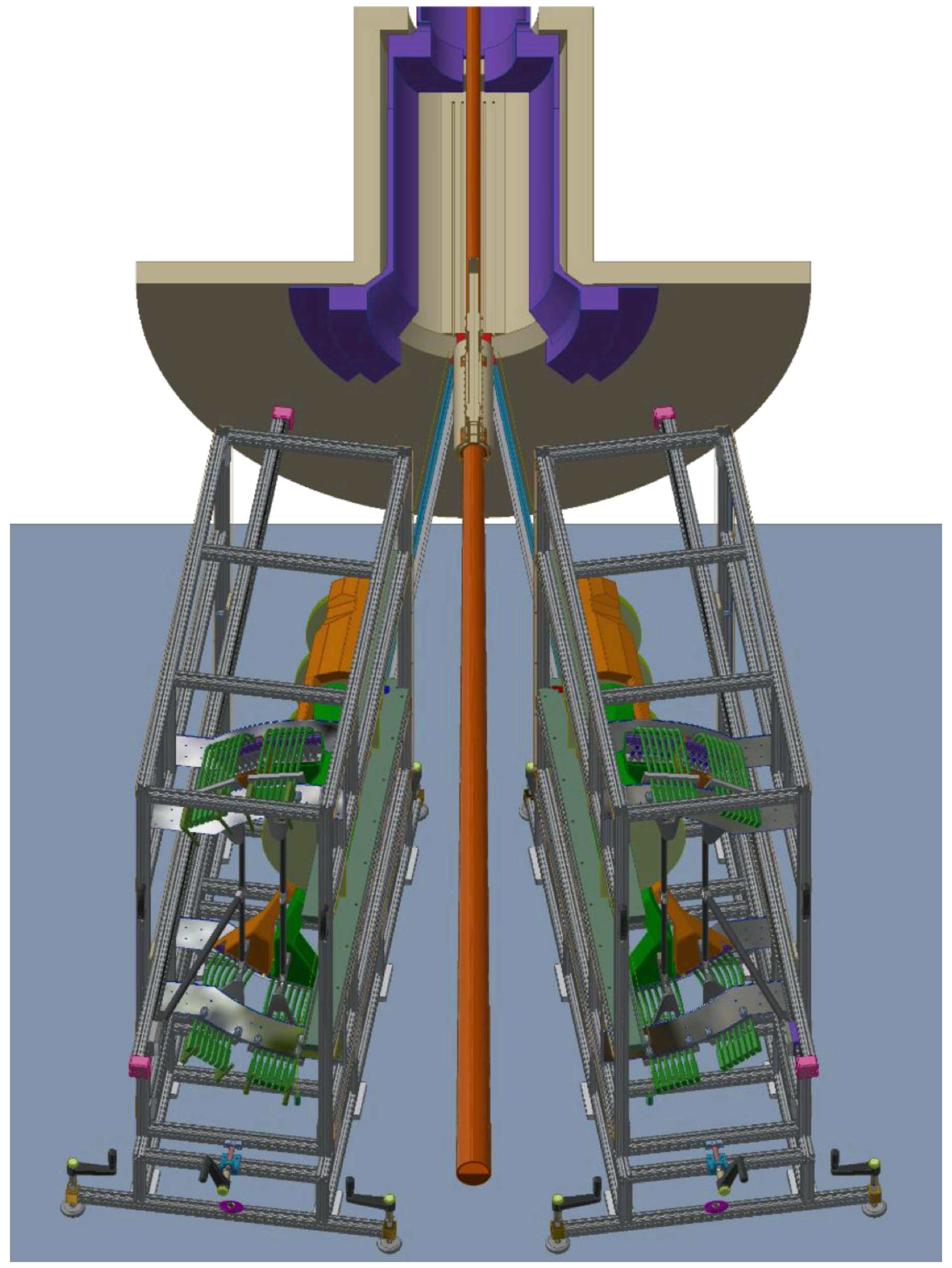




Disks have planar geometry

Barrel splits in half but central modules are staggered

Relatively simple removal/ installation [smaller L1 radius since beam pipe bake out can be done wo/ IT in place]



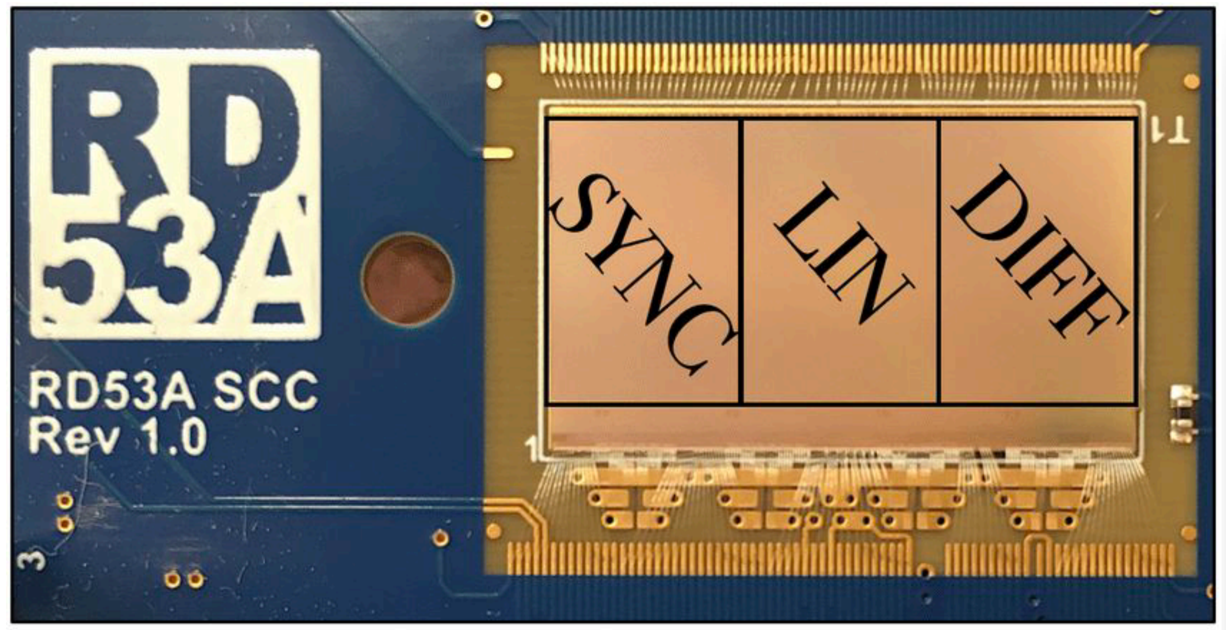
Example of installation/removal tooling (TEPX)

Building block: the CMS Readout CHIP [C-ROC]

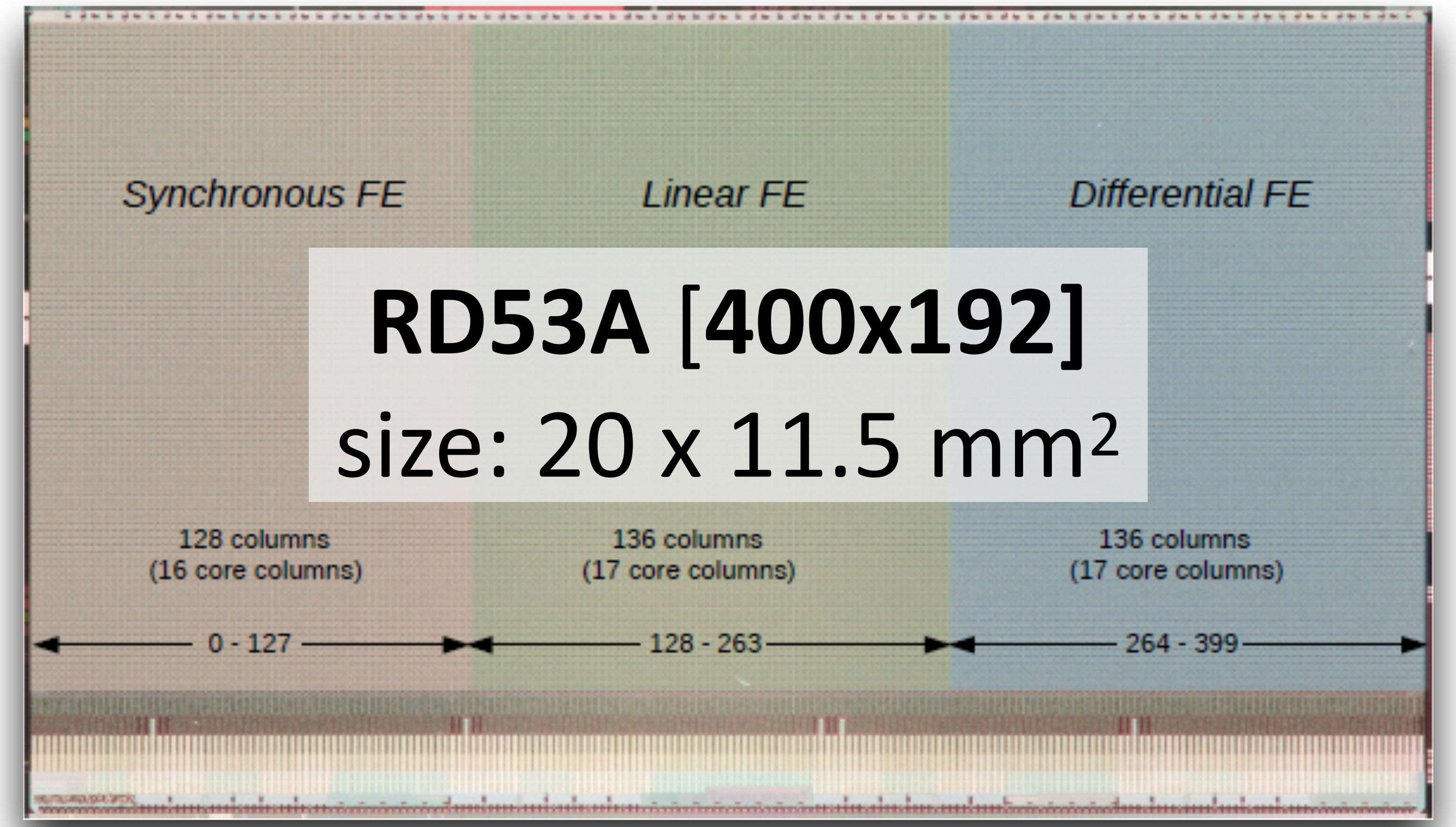
- Evolution of RD53A, the CROC is developed by the RD53 Collaboration, a joint ATLAS-CMS effort for HL-LHC pixel detectors readout chips
- Lot of effort ongoing to submit the production chips, now scheduled for November ‘22 (Atlas) and April ‘23 (CMS)

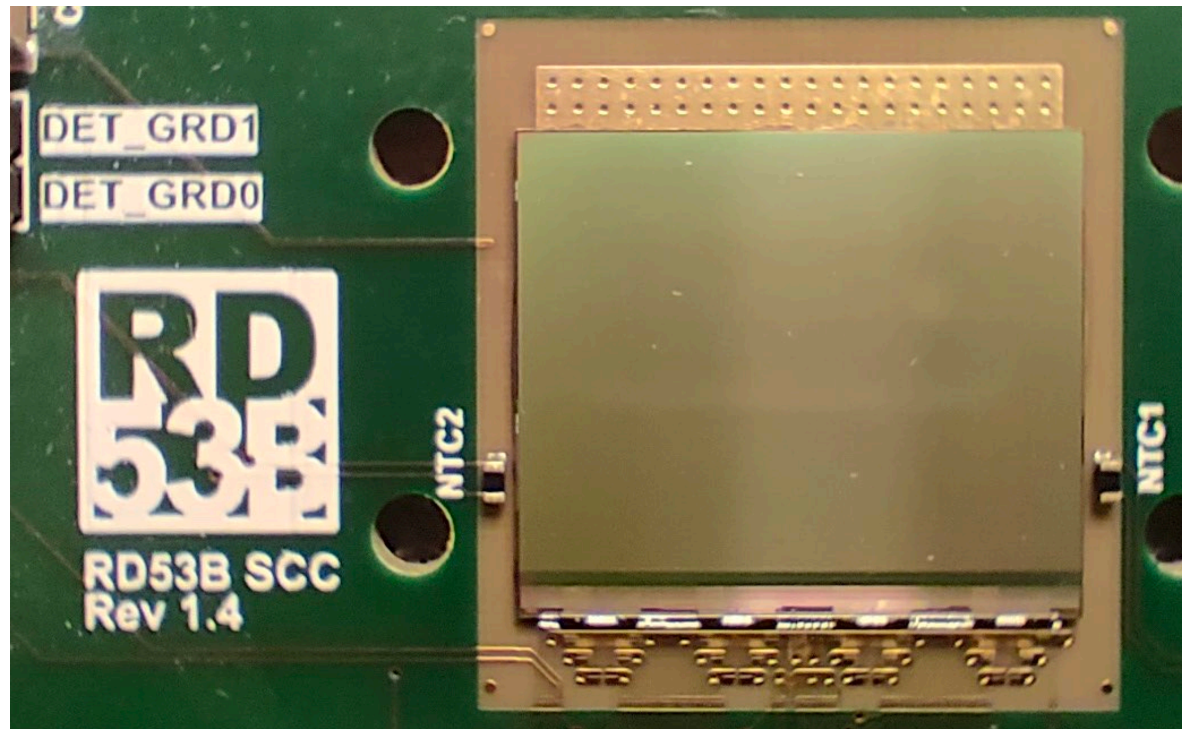
Cell size	50x50 μm^2
Technology	CMOS 65 nm
Hit rate	3.5 GHz/cm^2
Trigger rate	750kHz
Trigger latency	12.5 μs
Min. threshold	600 e-
Radiation tolerance	> 500 Mrad* @ -15 °C
Power	< 1W/cm^2

*but demonstrated working up to ~1.1Grad

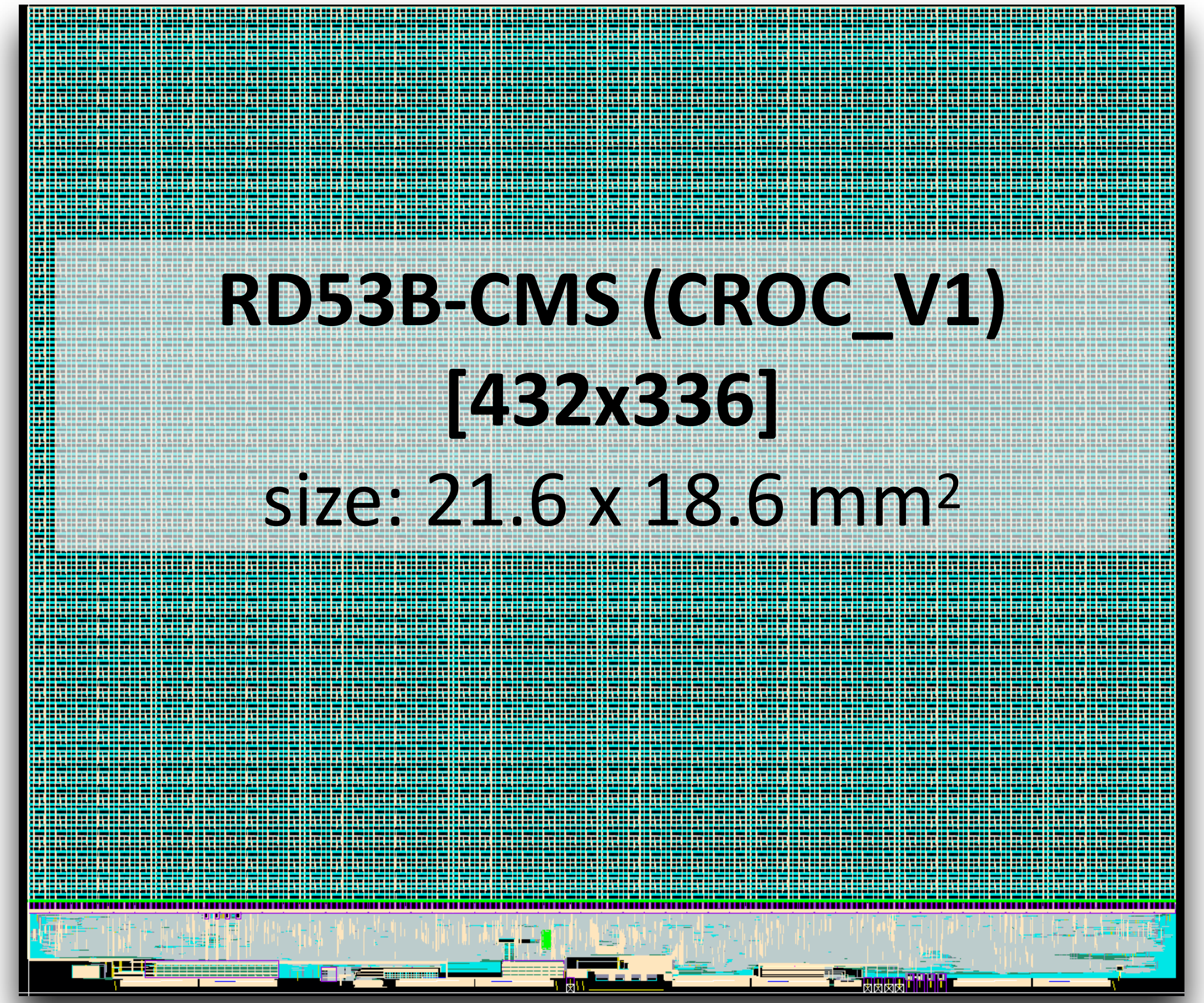


Common ATLAS/CMS prototype w/ three different FE architectures





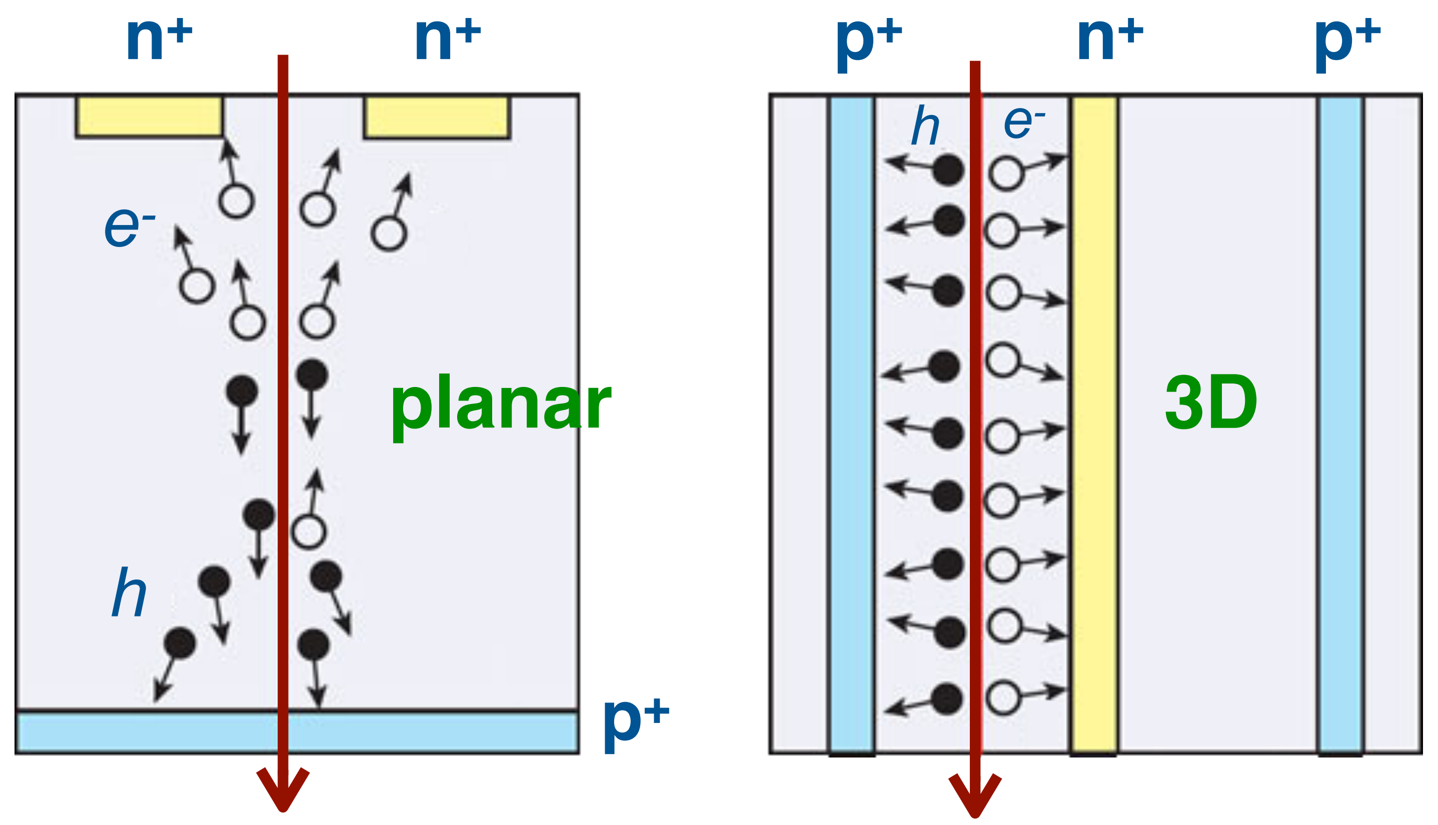
CMS prototype w/ final size and linear FE



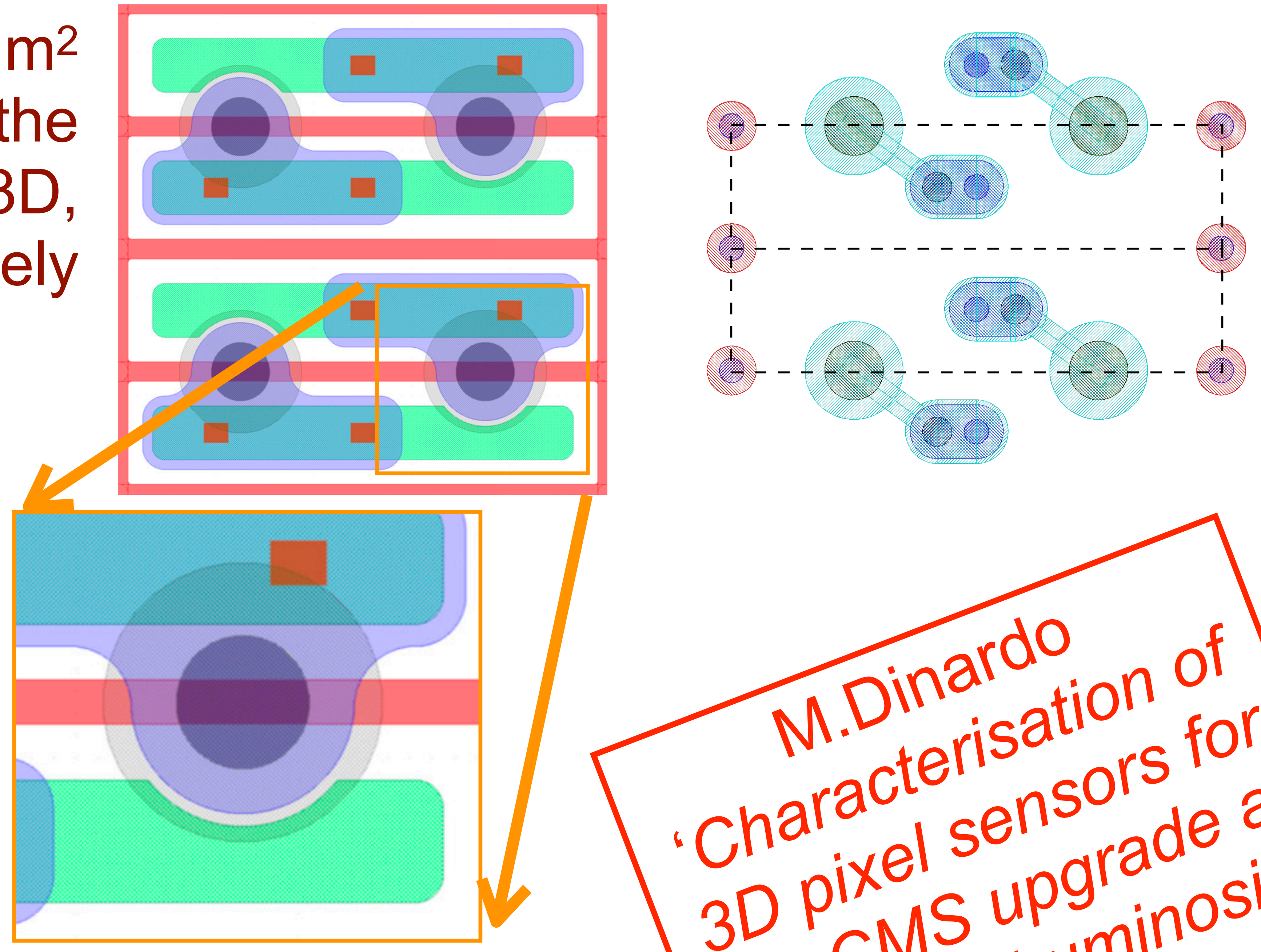
Building block: the pixel sensors for $>10^{16}neq/cm^2$

- Planar n-in-p sensors:
  - bias up to ~800V and spark protection between ROC and sensor.
  - Vendors: HPK, FBK & LFoundry; tendering is being completed!
- 3D sensors for barrel L1
  - Vendors: FBK & CNM; tendering in preparation
- 150µm bulk thickness, $25x100µm^2$ pixel cells [6x smaller wrt than current pixel phase-1]
  - bump bonding pattern is $50x50µm^2$
  - cross talk issues studied and minimized (i.e. bitten implant on planar)
- Extensive irradiation plus test beams (CERN, Desy, FNAL) campaign to establish radiation hardness of the sensor+ROC assembly!

The pixel planar and 3D concept

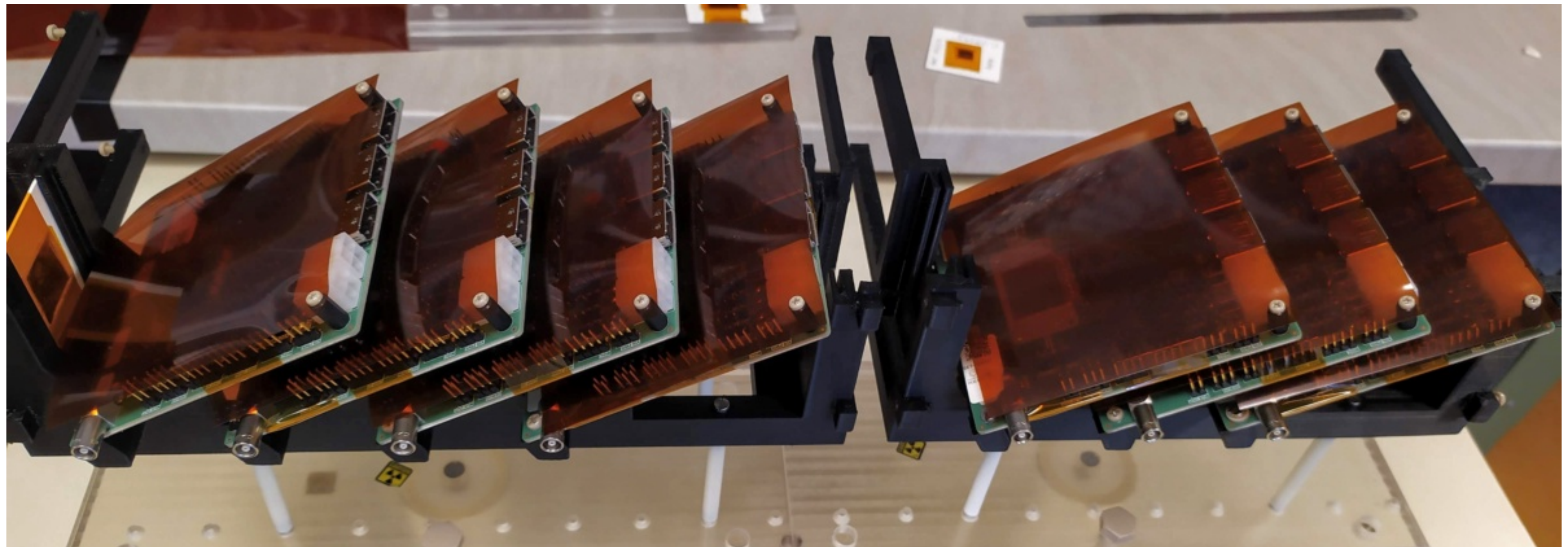


2x $25x100µm^2$ cells for the planar and 3D, respectively



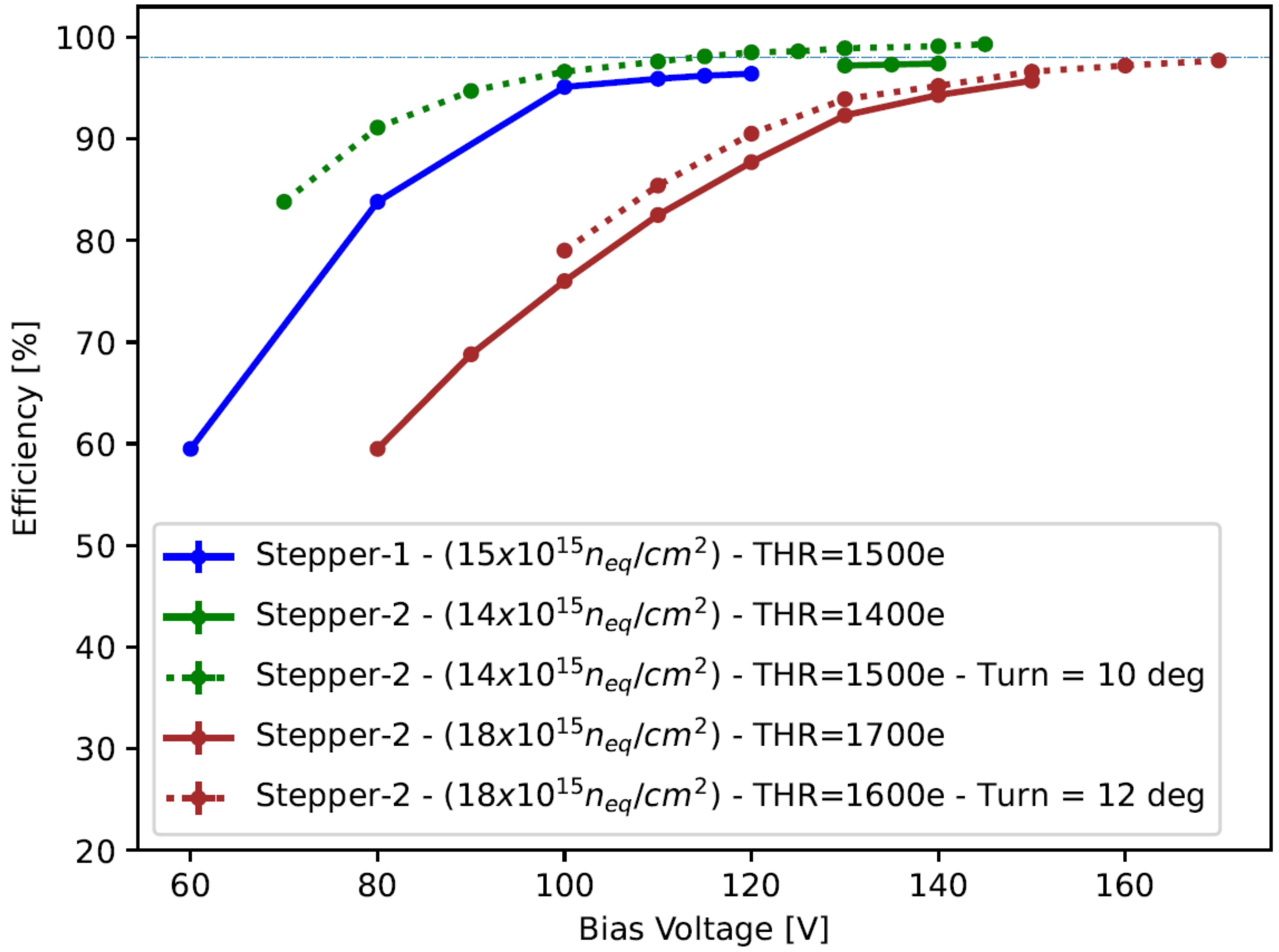
Detail of the anti-xtalk 'bitten' implant

Tray of C-ROC sensor modules arranged for irradiation @IRRAD

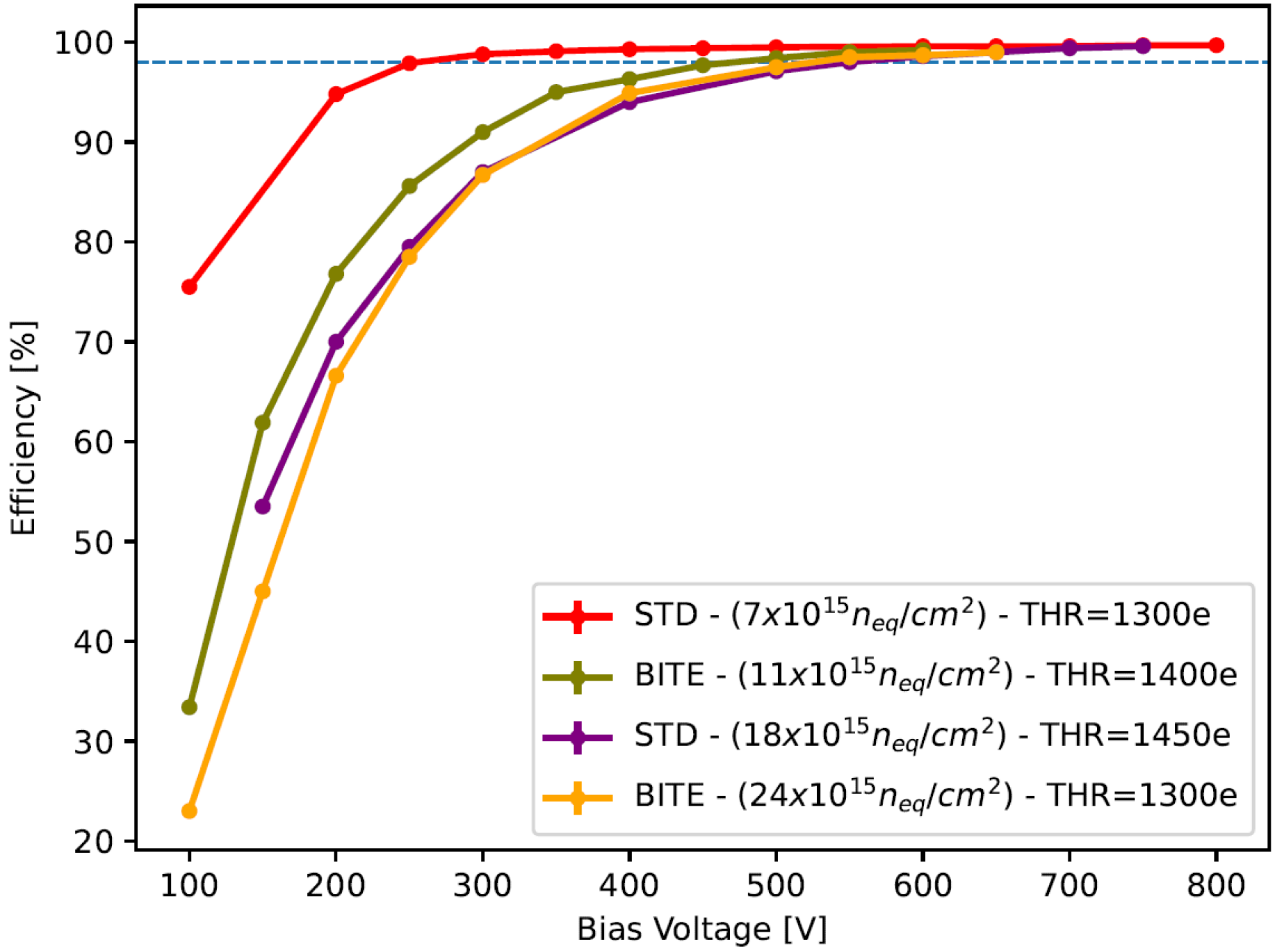


M.Dinardo 'Characterisation of 3D pixel sensors for the CMS upgrade at the High Luminosity LHC'

Sensor performance after irradiation



Irradiated (KIT) FBK 3D
[up to $1.8 \times 10^{16} n_{eq}/cm^2$]



Irradiated (KIT) FBK Planar
[up to $2.4 \times 10^{16} n_{eq}/cm^2$]

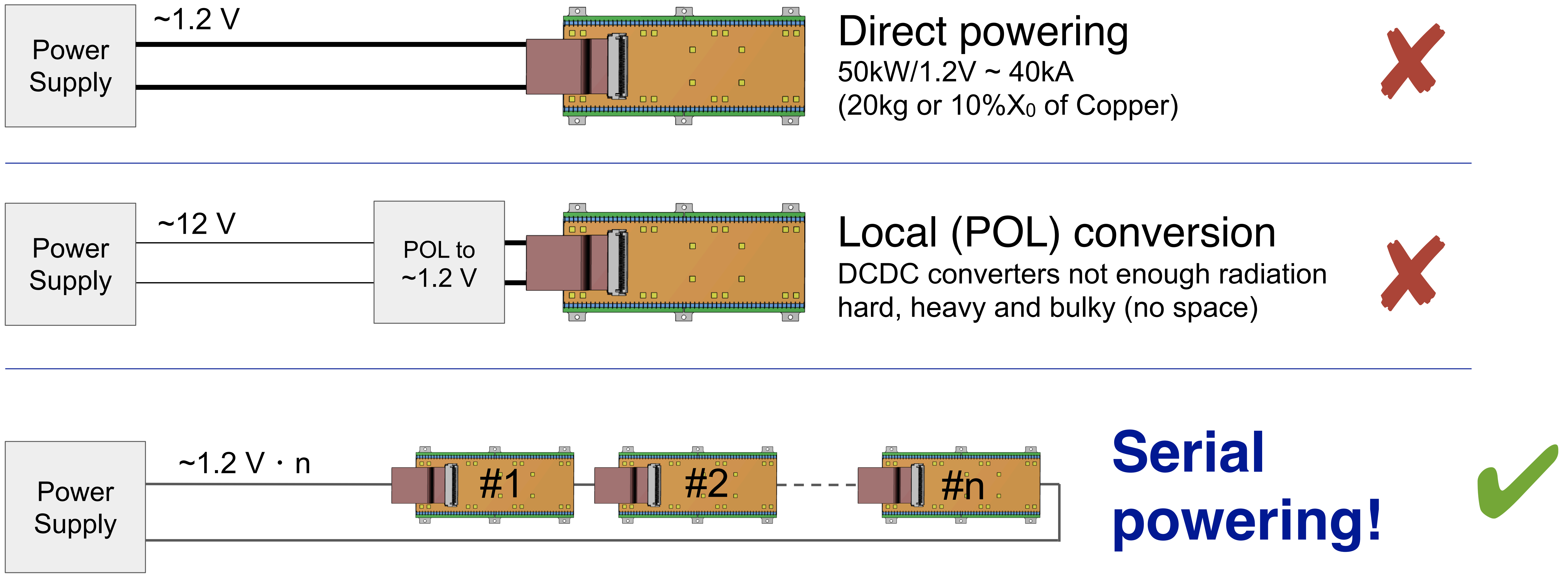
Getting the power in and out the IT

design choices

- **High Granularity**
- **CMOS @65nm** ASICs (radiation resistant but low operating voltage)
- **Large area**
- **Large Bandwidth**
- **Small collected charge (thin sensors)**

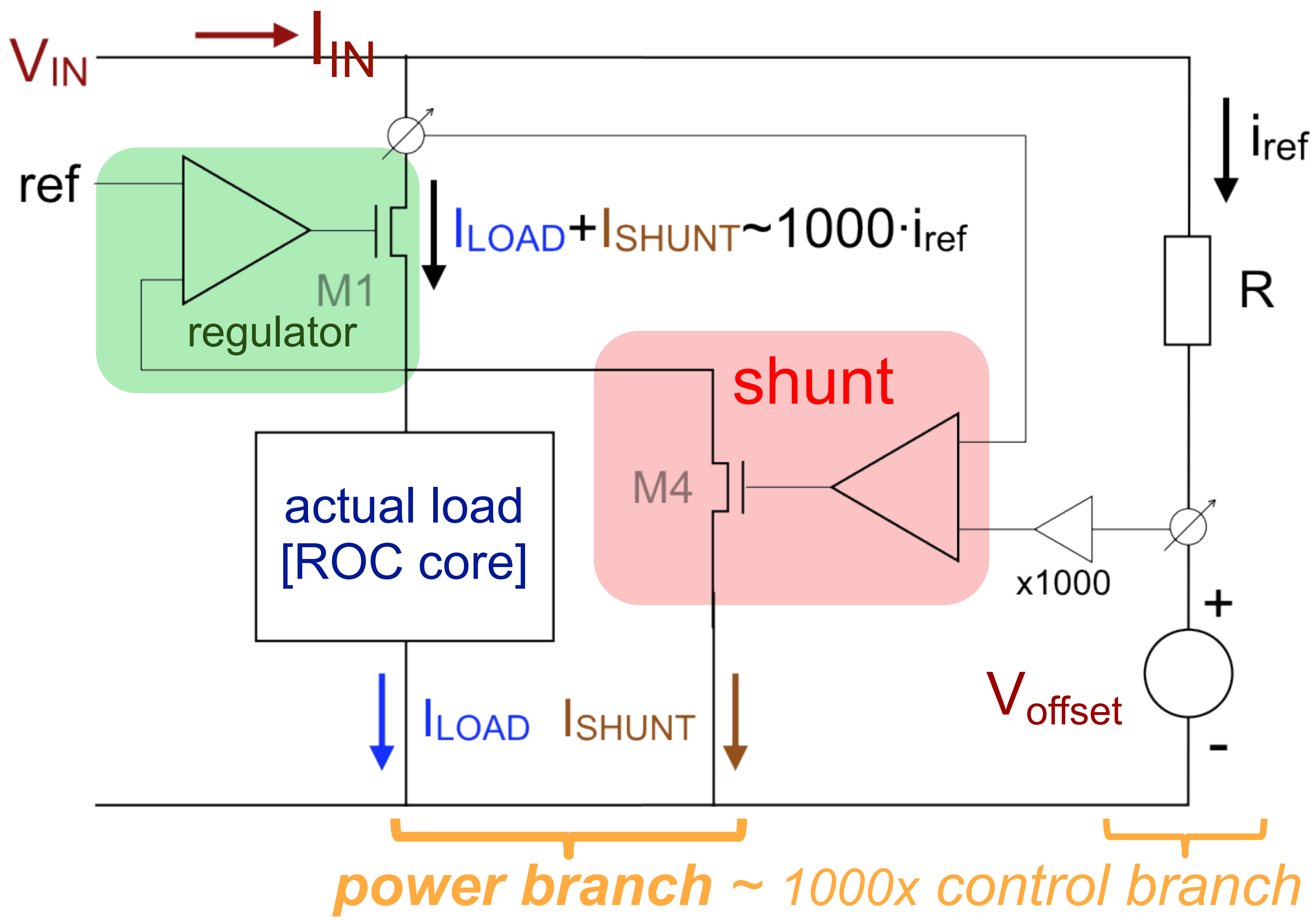
- Large consumption of digital circuitry (bandwidth) and analog circuitry (low threshold and low noise)
- 2 billions channels

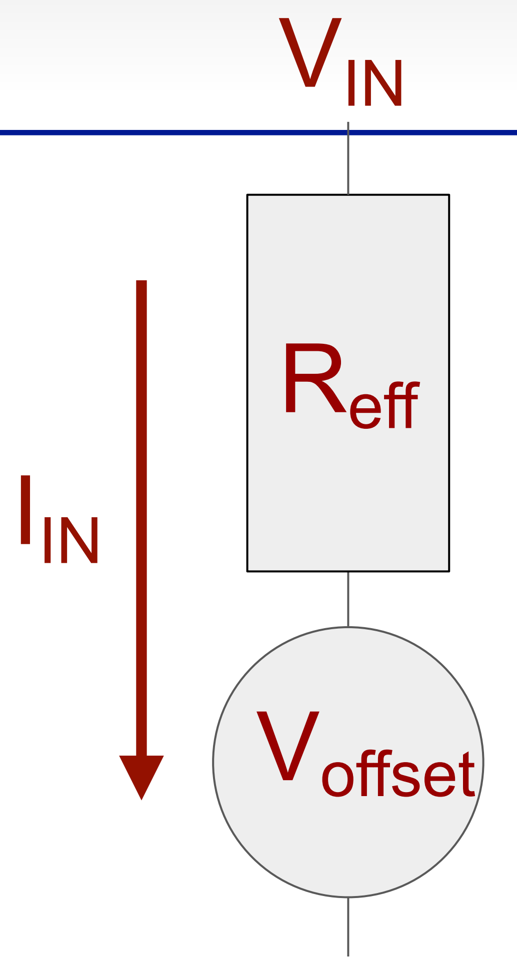
Very large power budget: ~50kW @~1.2V

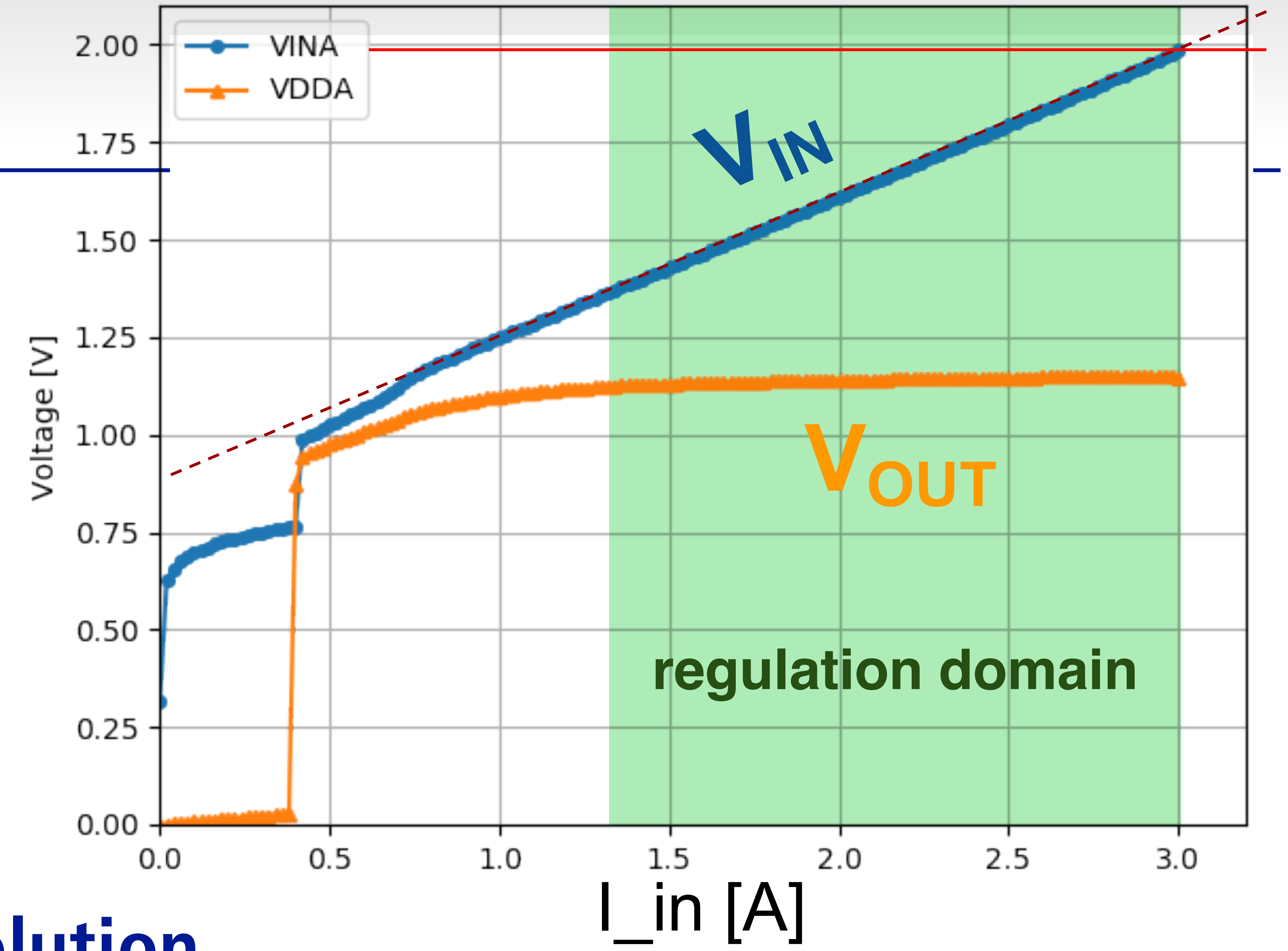


- **POWERING**: only serial powering is compatible HL-LHC for IT
  - major technological challenge: never been used on large scale.
  - all chain elements see the same current (by construction); voltage is equally shared if all elements represent **the very same and constant load**…
- **COOLING**: two-phase -30^{o}C CO^{2} cooling system;
  - for the entire IT+OT: 5x 50kW cooling plants for redundancy, one always in stand-by

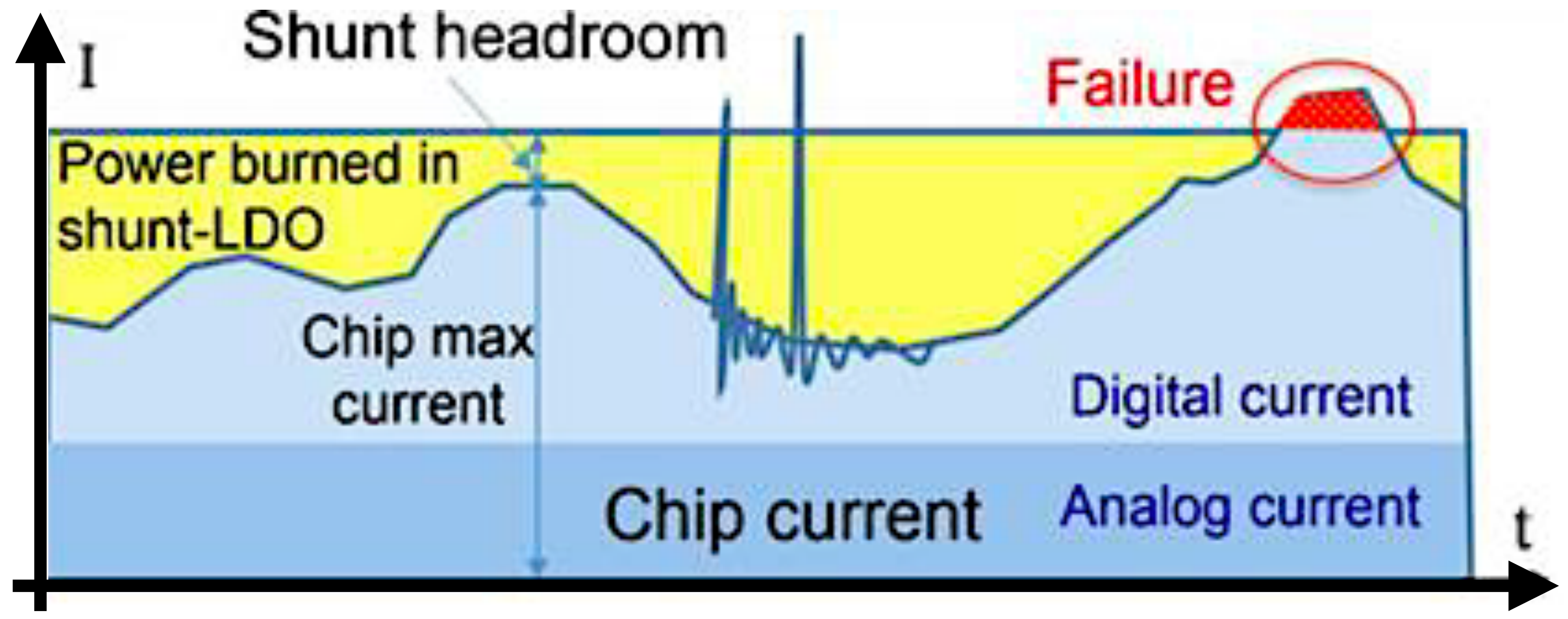
SP with the ShuntLDO

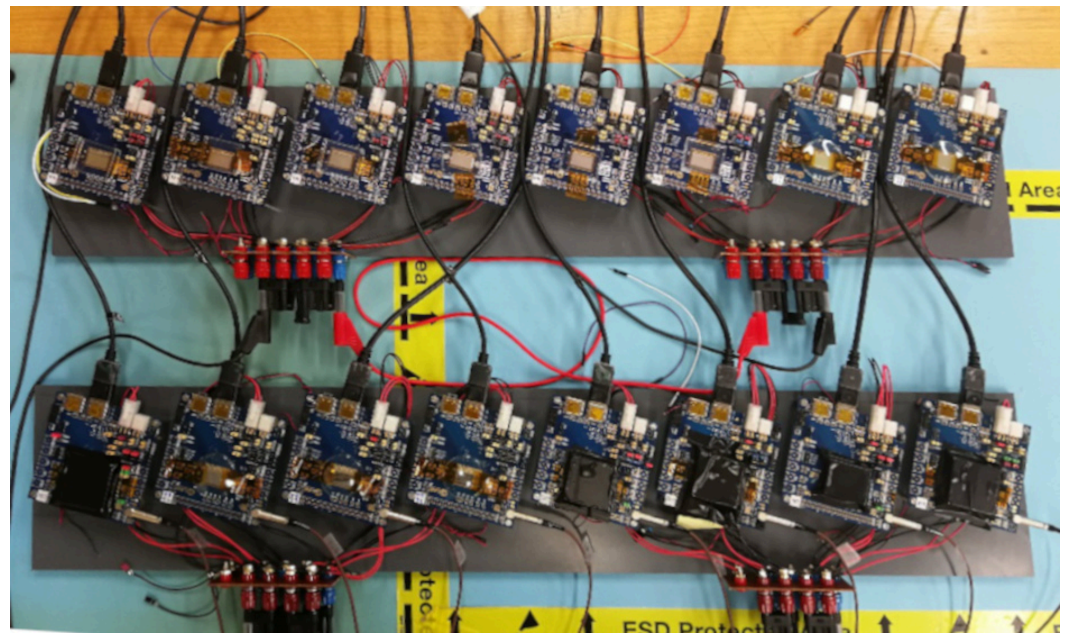






- Integrated **on-chip solution**
  - Low mass, Radiation hard, no extra ASICs
- **Equivalent to a resistor** in series with a voltage source
  - Healthy behavior in parallel configuration (Digital and Analog domains in the same chip and on chips on the same modules)
- **Each module has its own local ground**
  - impacts HV distribution to sensors and I/O must be in AC
- Needs some overhead power





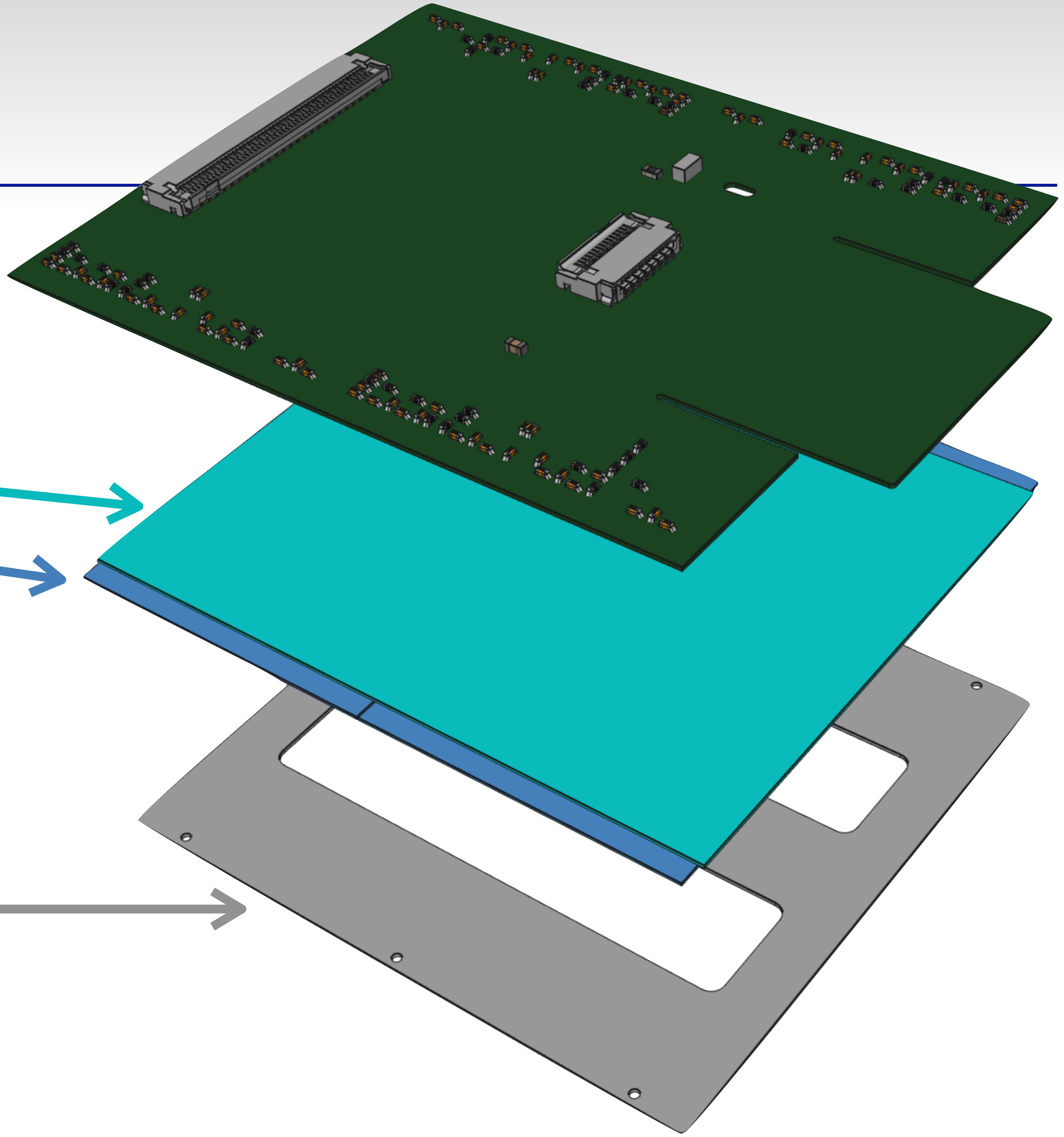
IT module structure

HDI
[high density interconnect]

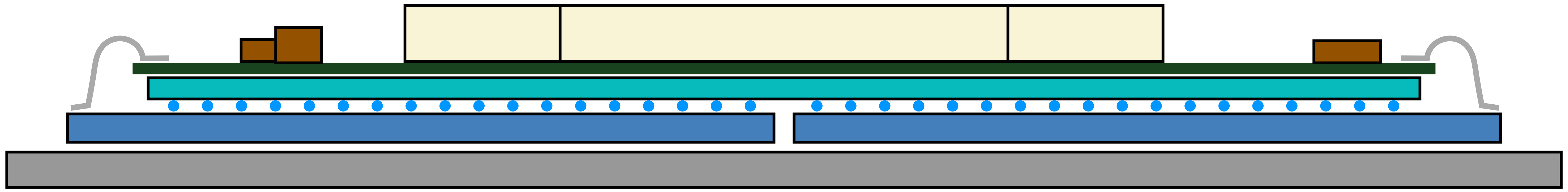
The HDI is a completely passive object (connectors, filters, line terminations…)

Sensor
+ ROCs
assembly
[aka bare module]

Aluminum Nitride rail
[if present]



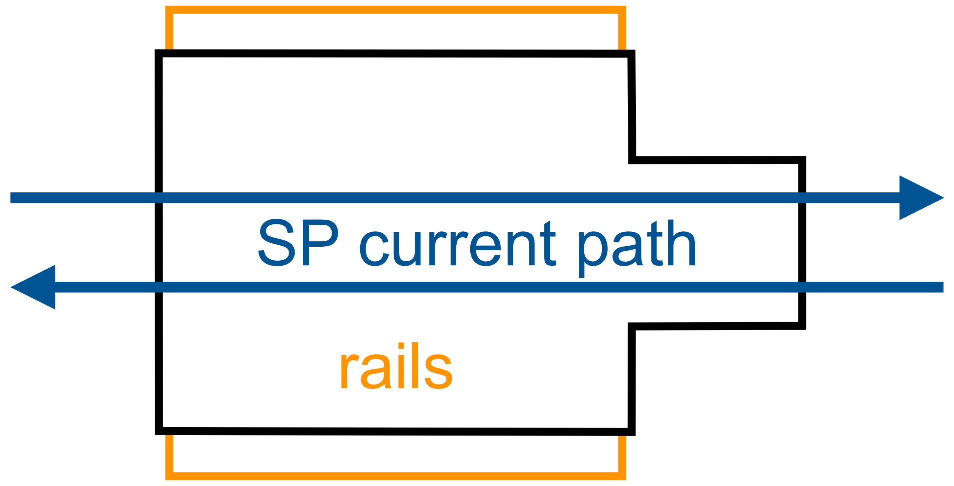
Exploded view of a TBPX 2x2 C-ROC module



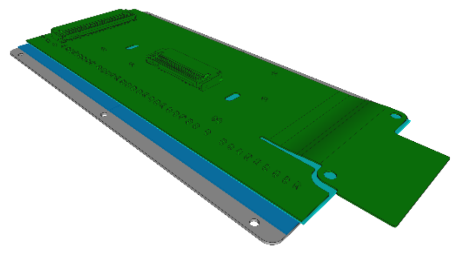
Transverse view of a TBPX 2x2 C-ROC module [not in scale]

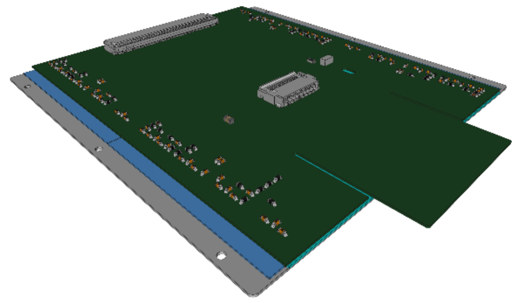
Module zoology

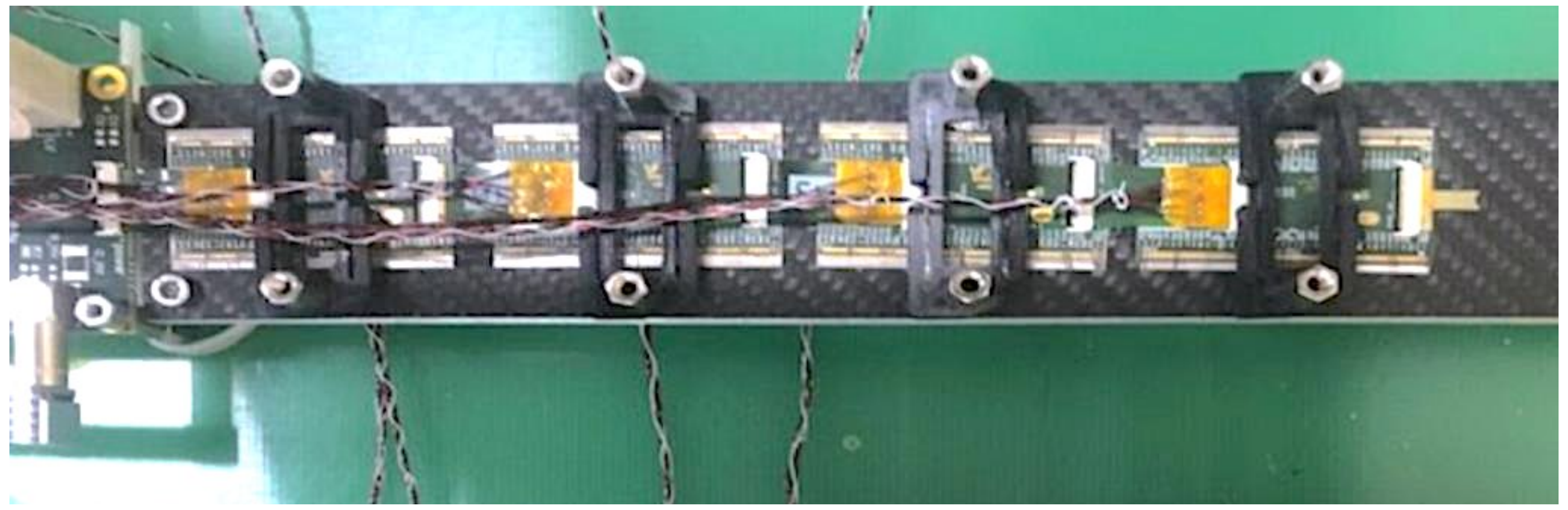
TBPX BARREL
1x2 2x2



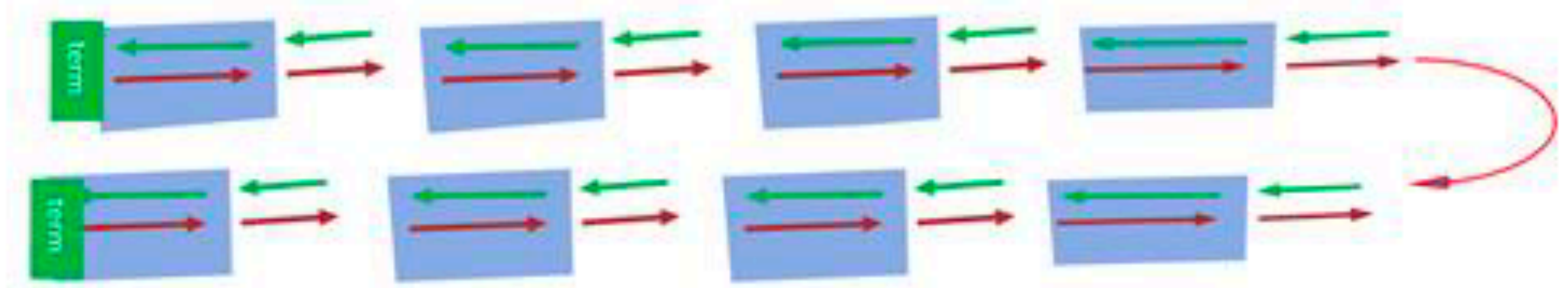
CROC modules



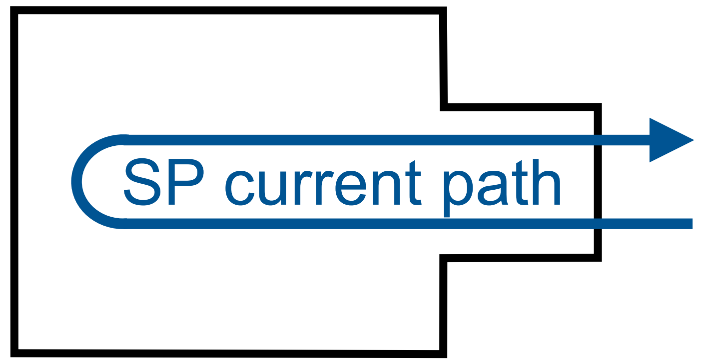


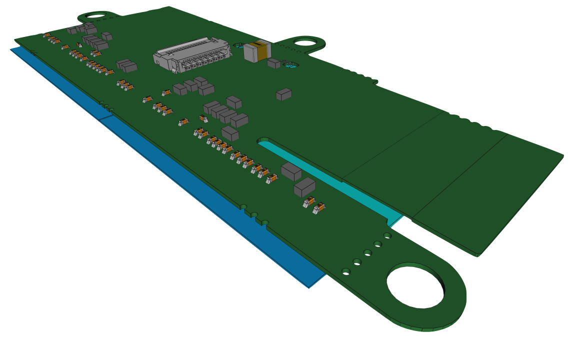


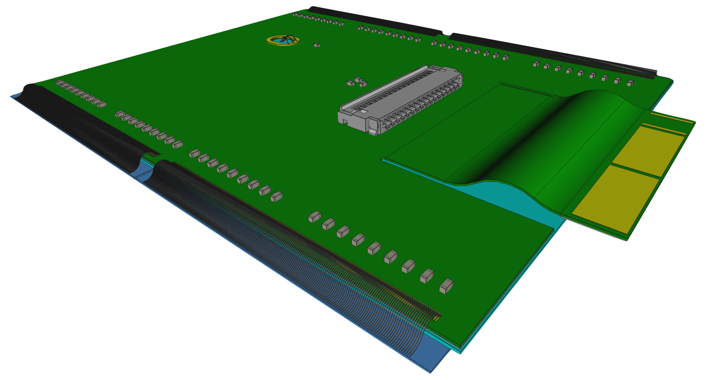
A prototype ladder

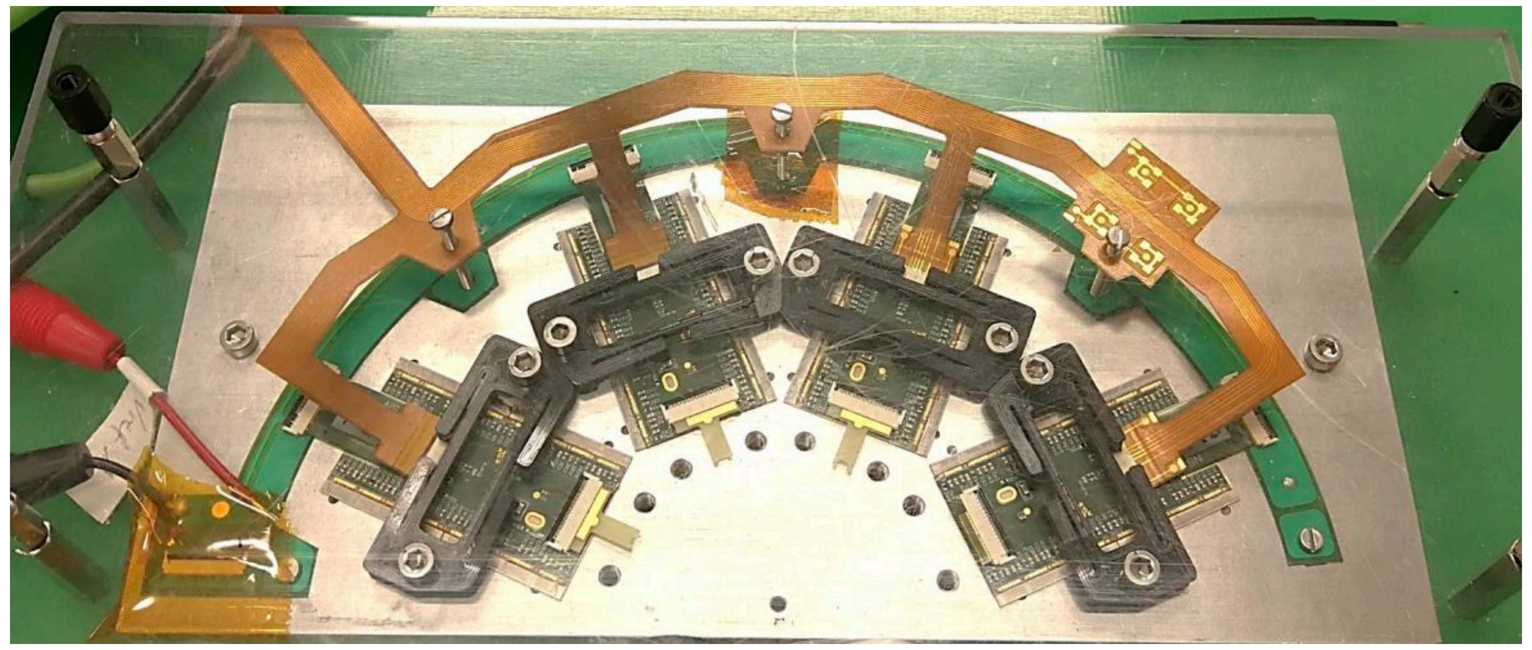


TFPX SMALL DISKS
1x2 2x2

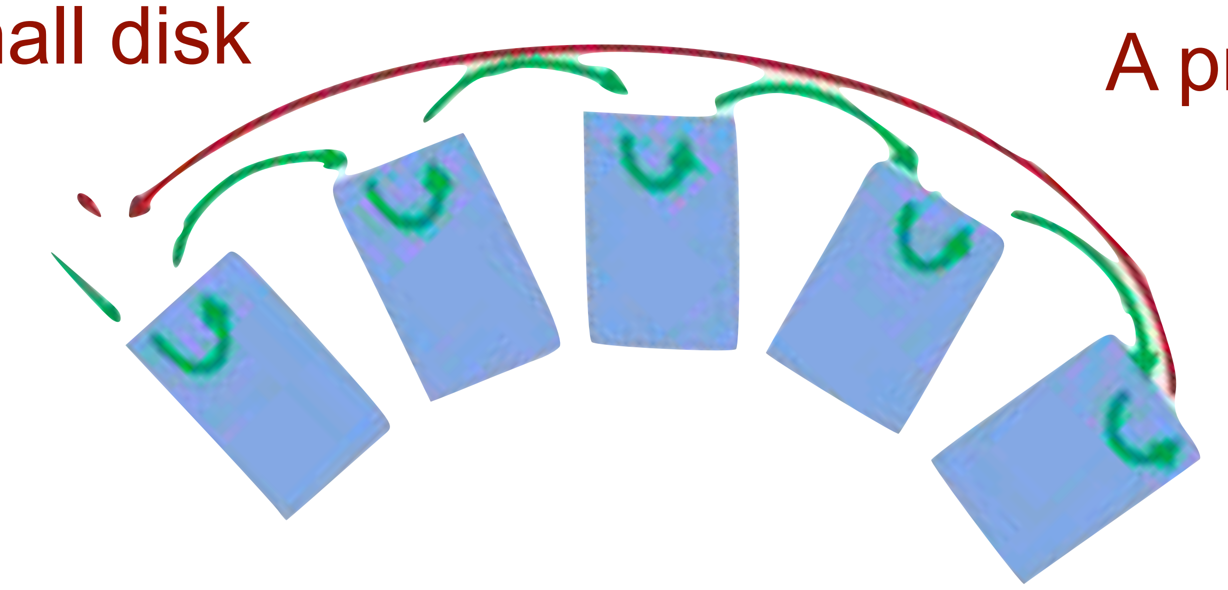




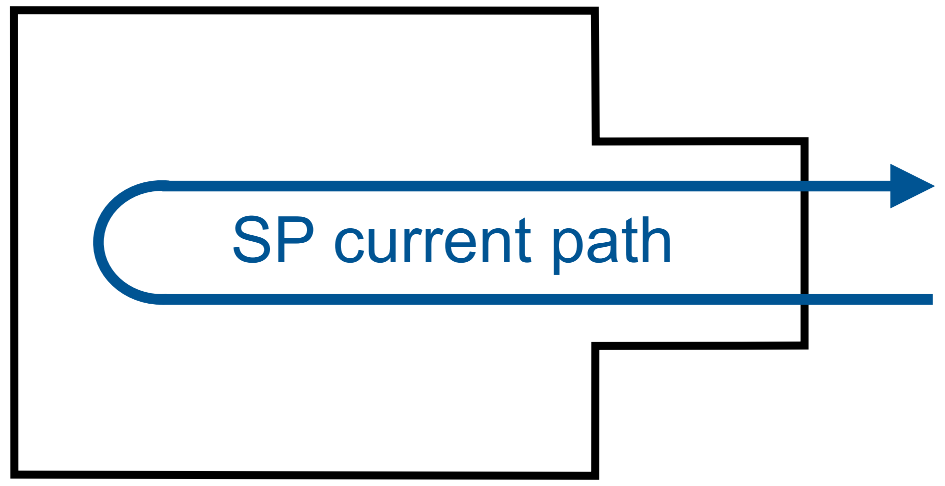


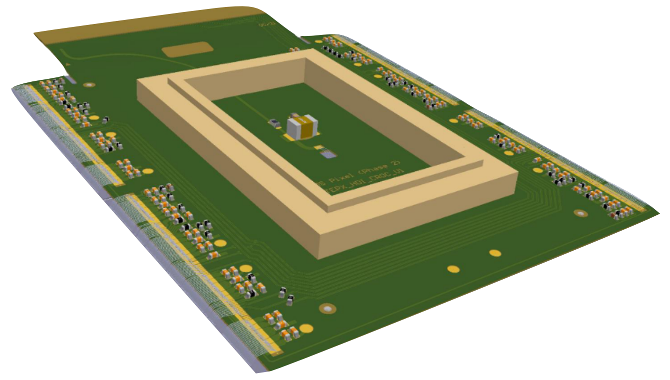


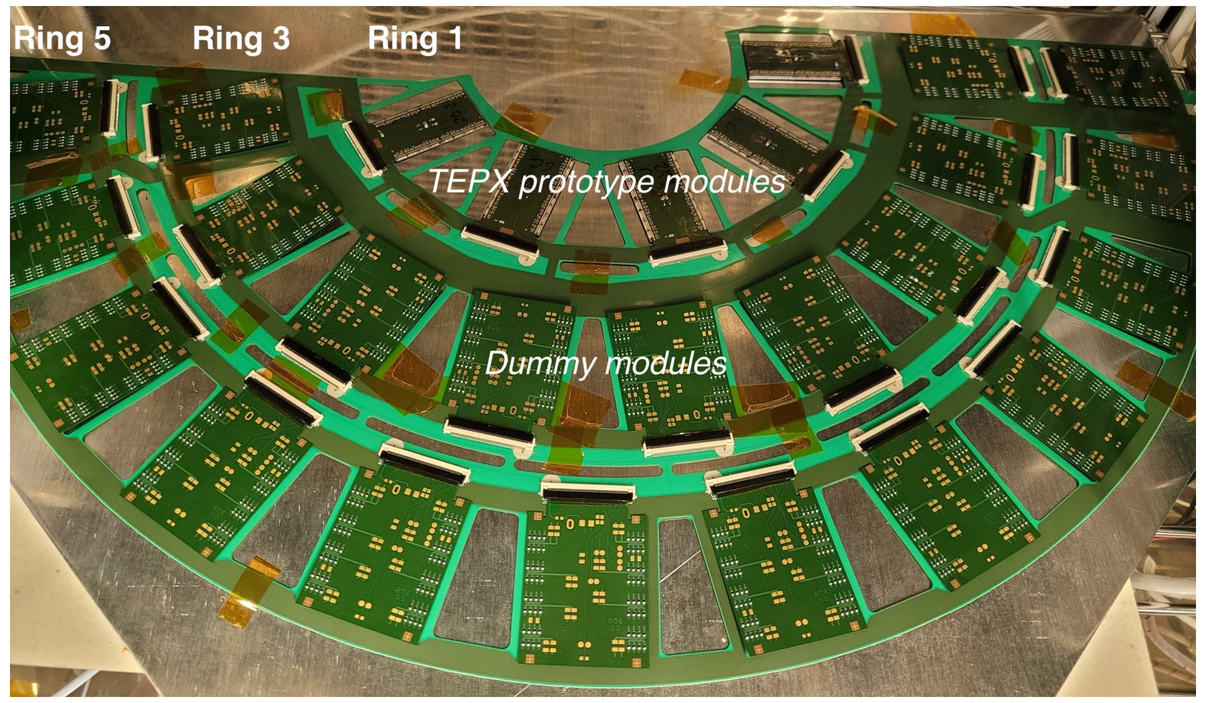
A prototype small disk



TEPX LARGE DISKS
2x2

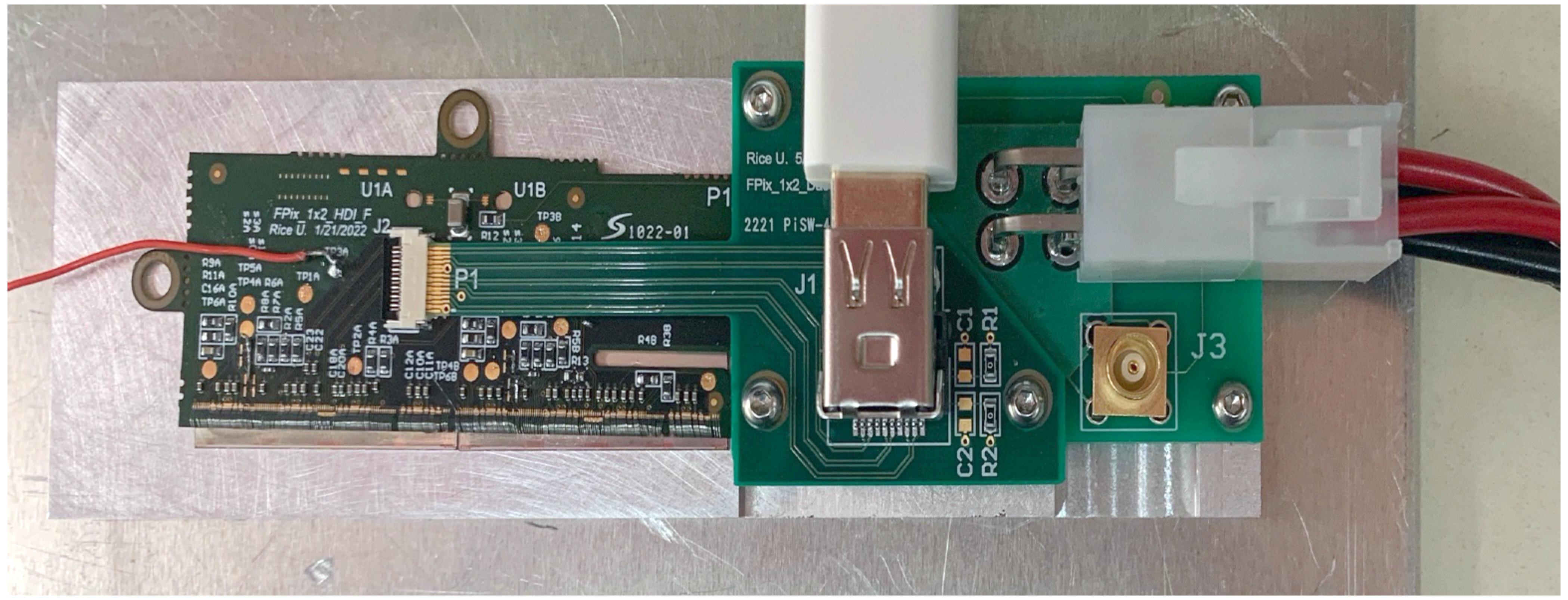






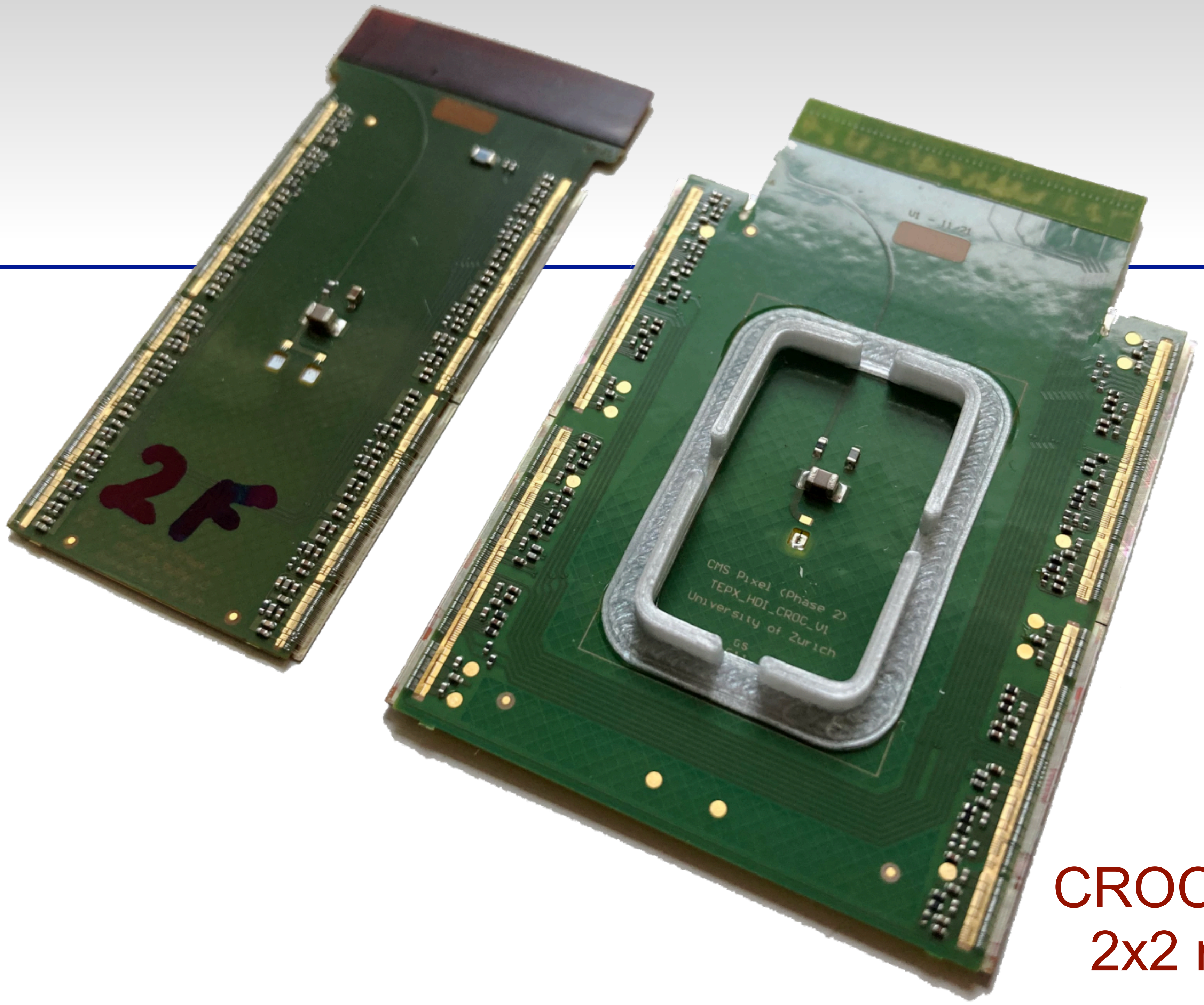
A prototyoe large disk

Module picture gallery



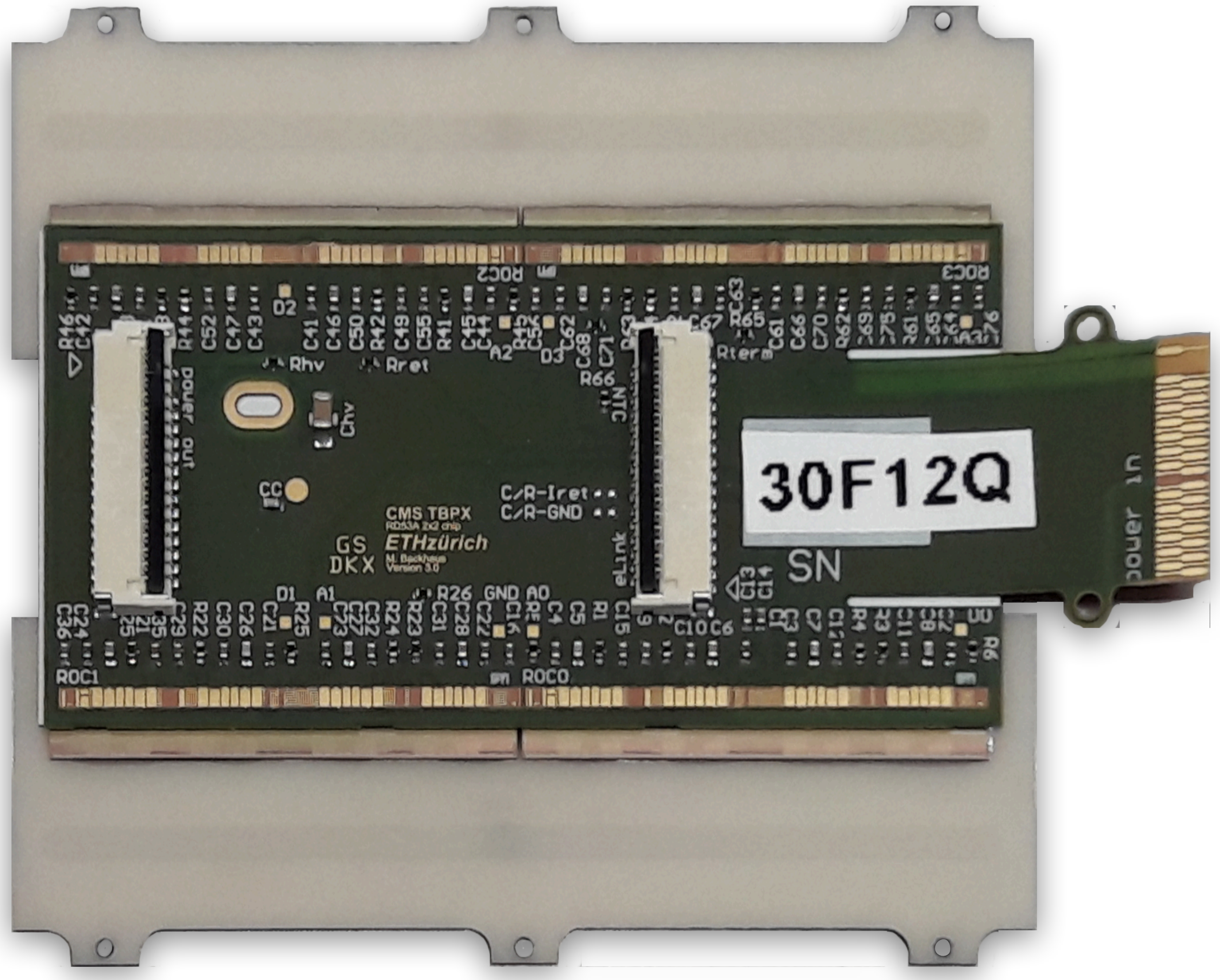
TEPX CROC digittal 1x2 module on the test setup

TEPX
RD53A 2x2
module

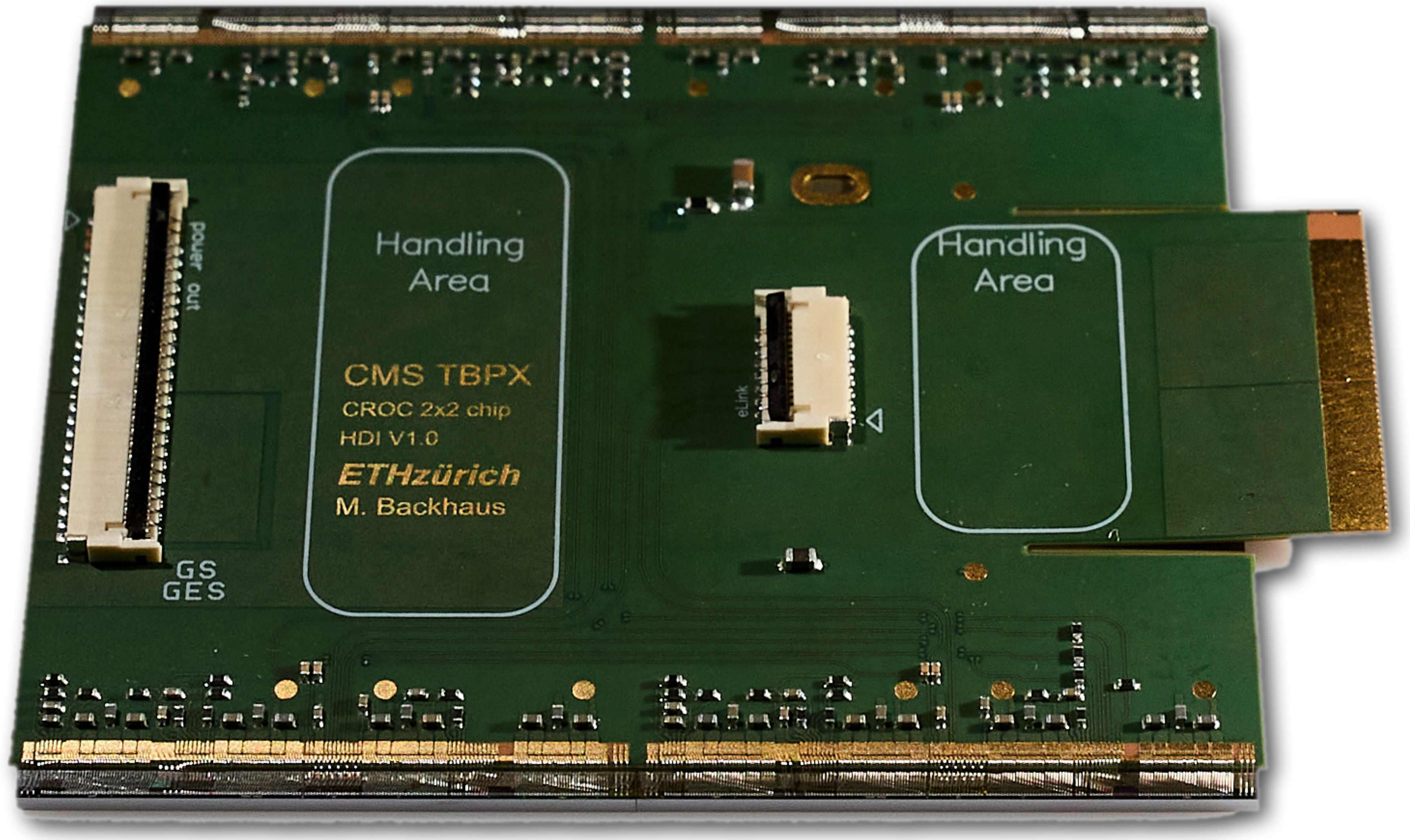


TEPX
CROC digital
2x2 module

RD53A TBPX digital 1x2 module



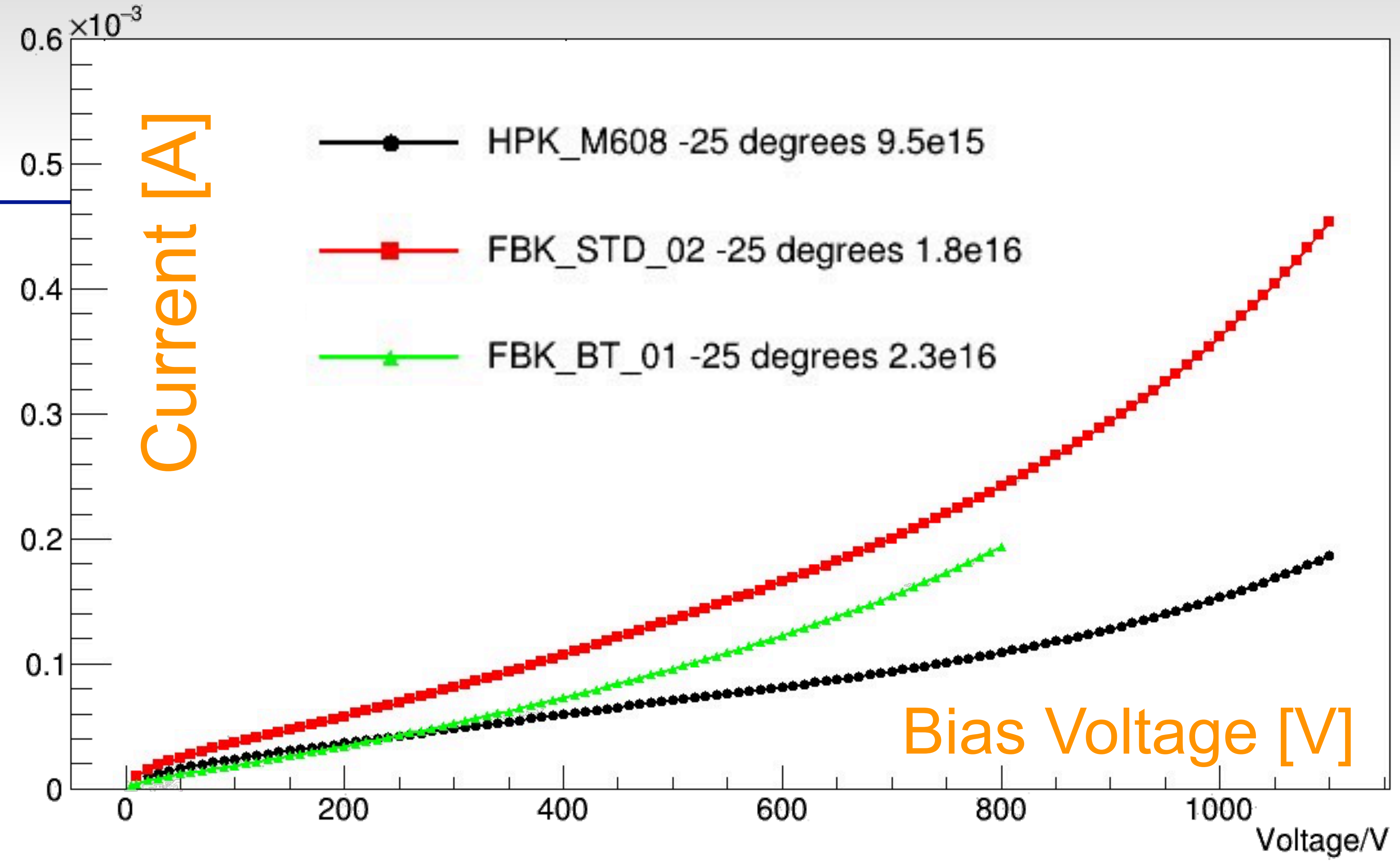
RD53A TBPX 2x2 module w/ rails



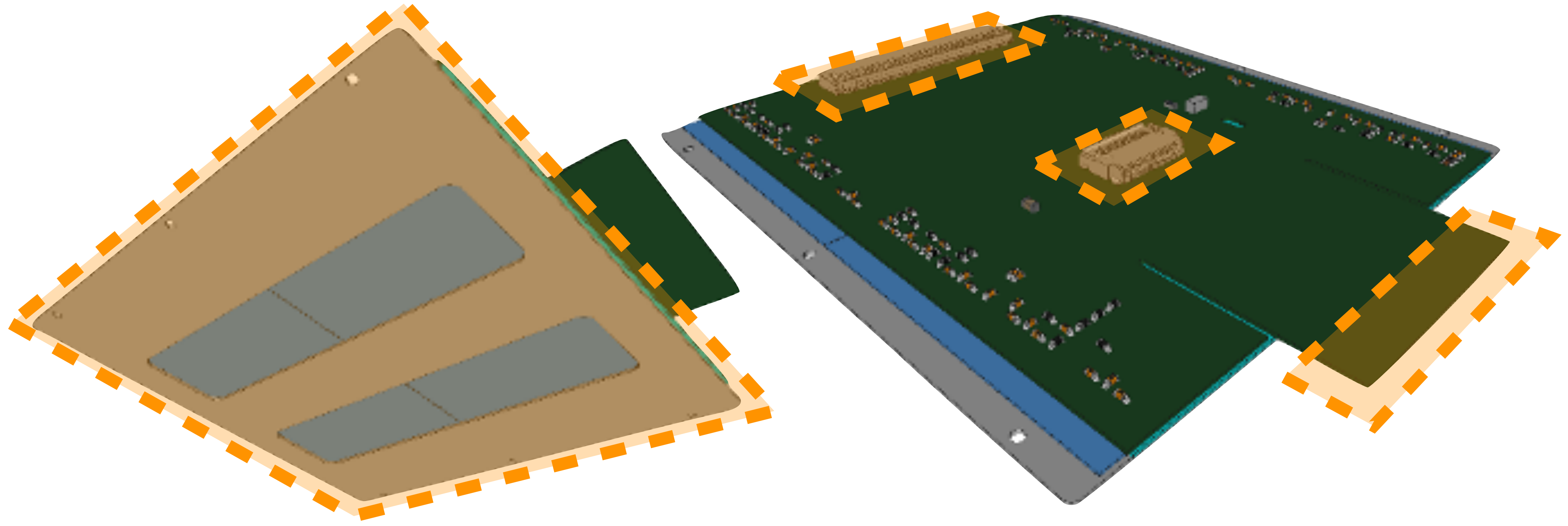
TBPX CROC digital 2x2 module

Parylene coating

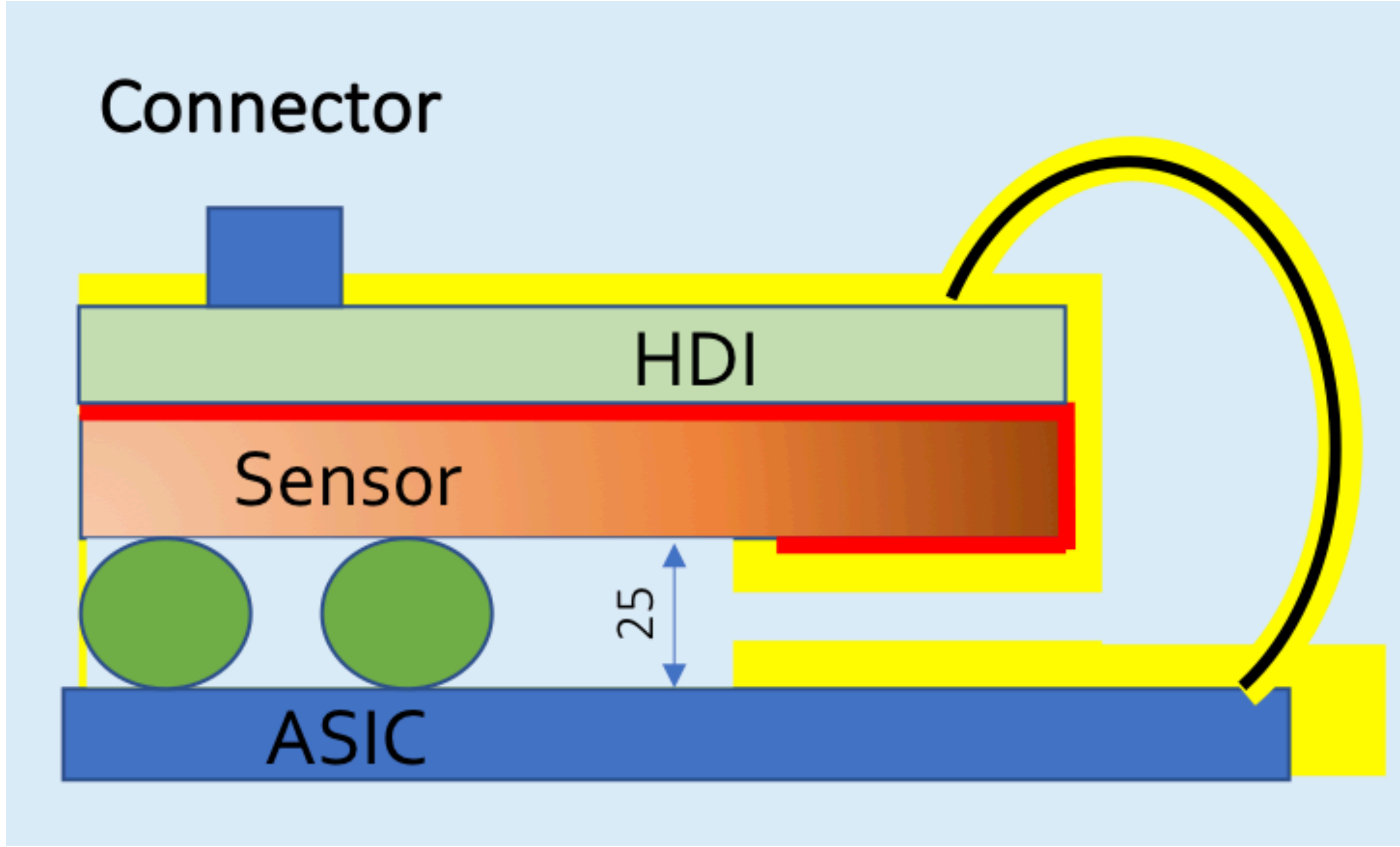
- Planar sensors modules: spark protection treatment to withstand HV bias up to 800V after irradiation
- Coating with Parylene-N (18µm thickness) from SCS Coating
  - Irradiation tests performed on single ROC+sensor assemblies up to $2.3 \times 10^{16} neq/cm^2$
  - Measured and thermally cycled in the climatic chamber and/or beam tests up to 1kV+
- In production the coating will be applied on the assembled multi-chip modules
  - full module coating already validated on prototypes
  - new step involving extra shipments and logistics
  - masking is needed fo connectors and pigtails (and backside if thermal performance is critical)



Post-coating, post-irradiation IV of HPK and FBK single chip modules



TBPX 2x2 C-ROC module with the regions to be masked during coating

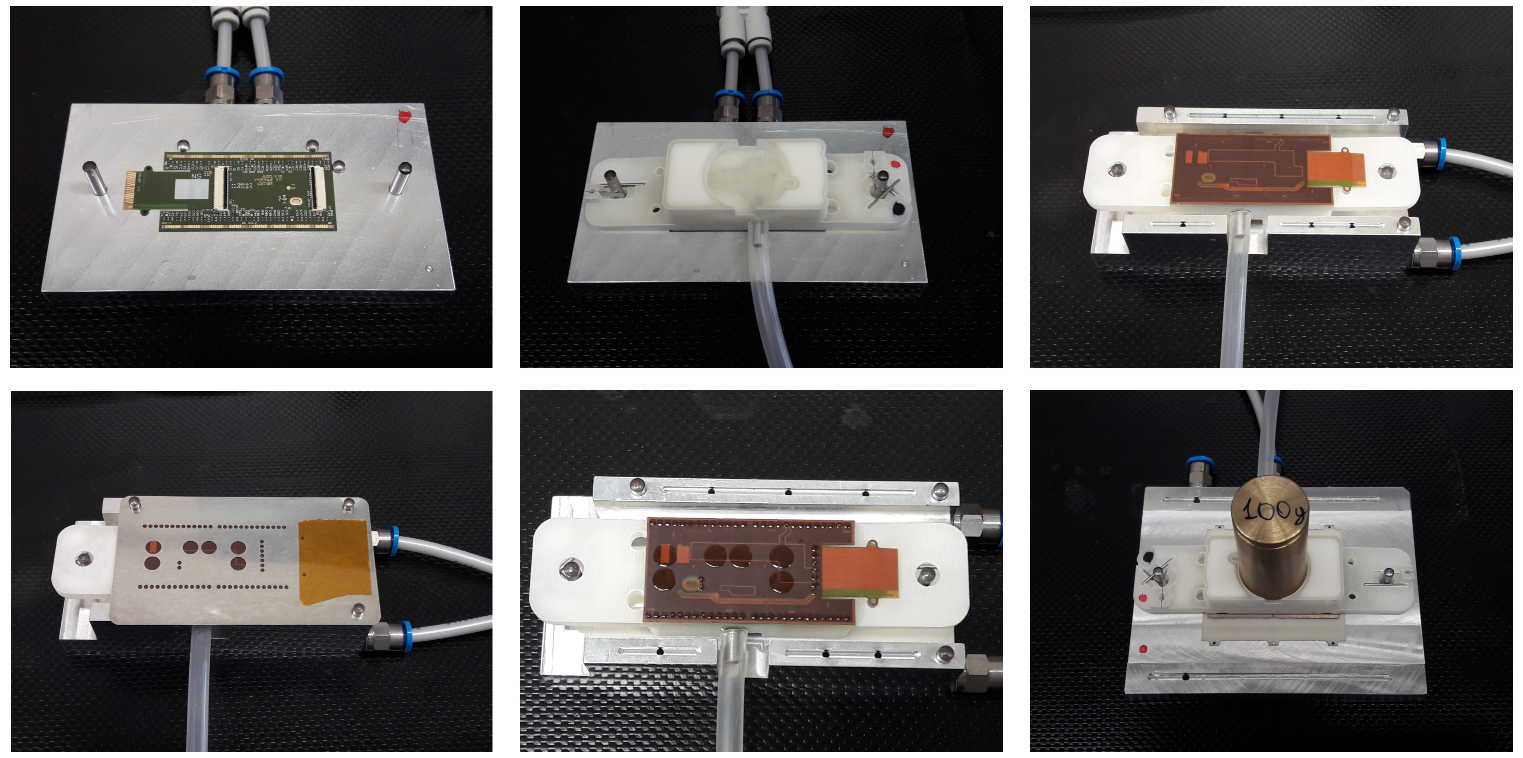


Sketch of the coating working principle

Module assembly

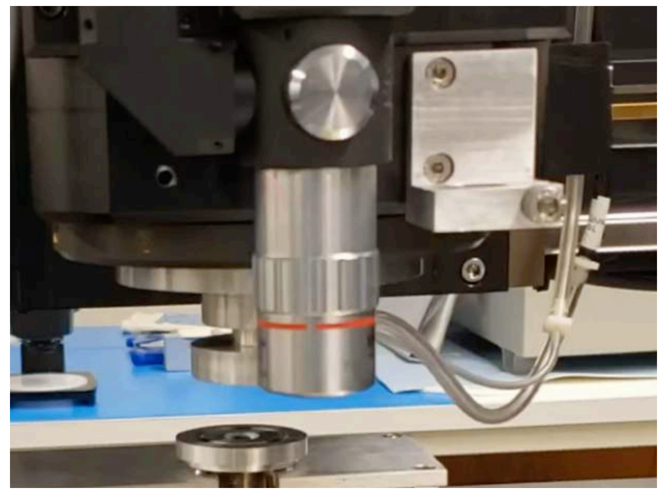
For all approaches we have demonstrated an assembly accuracy in the 10 to 20µm range

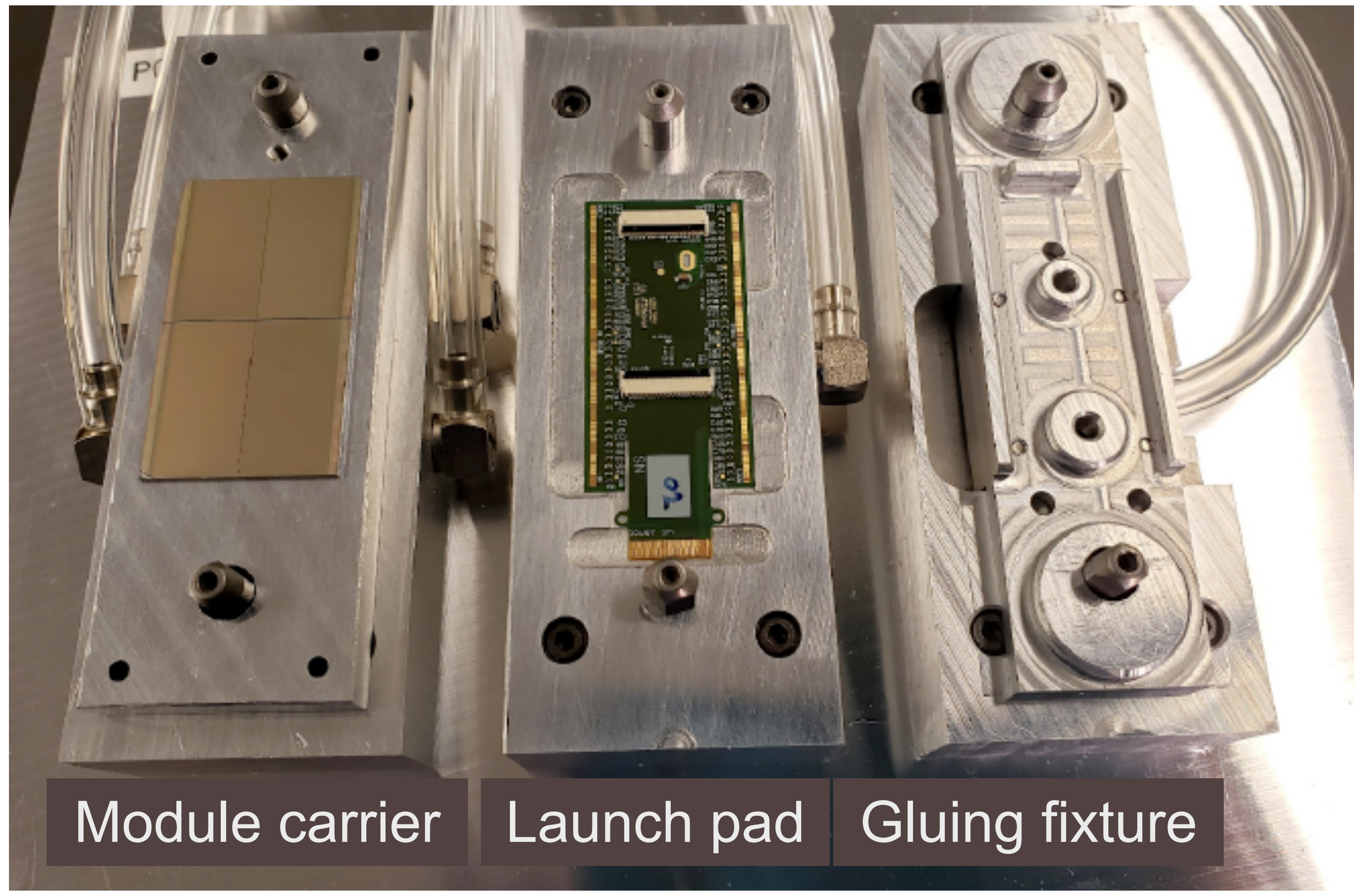
- TBPX - barrel
  - manual assembly with jigs and templates
  - glue distribution by using stencils
  - one extra assembly step for the rails
  - throughput by parallelization



A typical jig-based assembly sequence for a TBPX RD53A demo-module

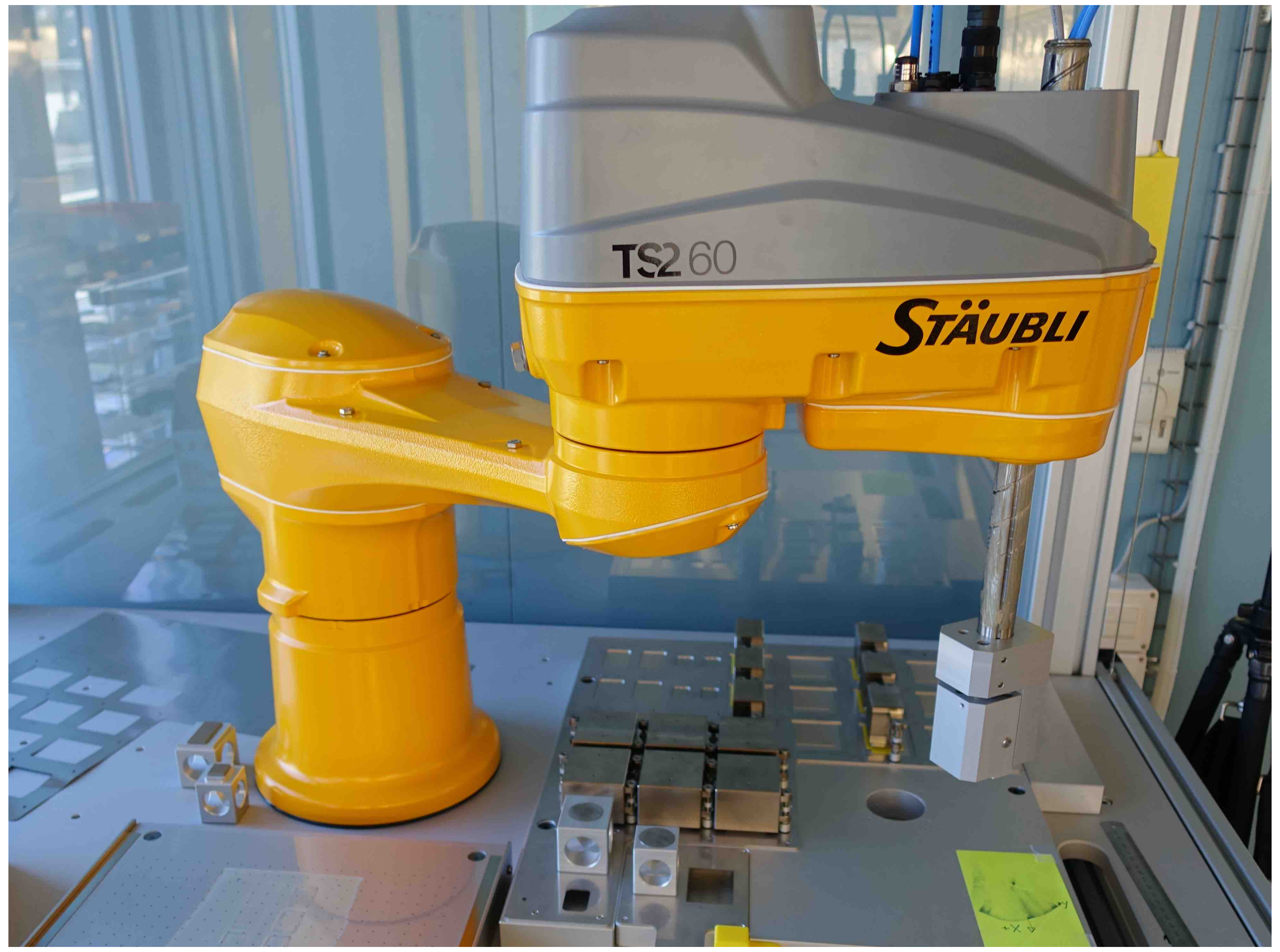
- TFPX - small disks
  - assembly by jigs and templates but parts placed by using a gantry that corrects for position with respect to reference markers
  - same tooling in all TFPX assembly centers
  - glue distribution by using stencils
  - throughput by parallelization





Assembly jigs in the TFPX/US community and a the gantry optics

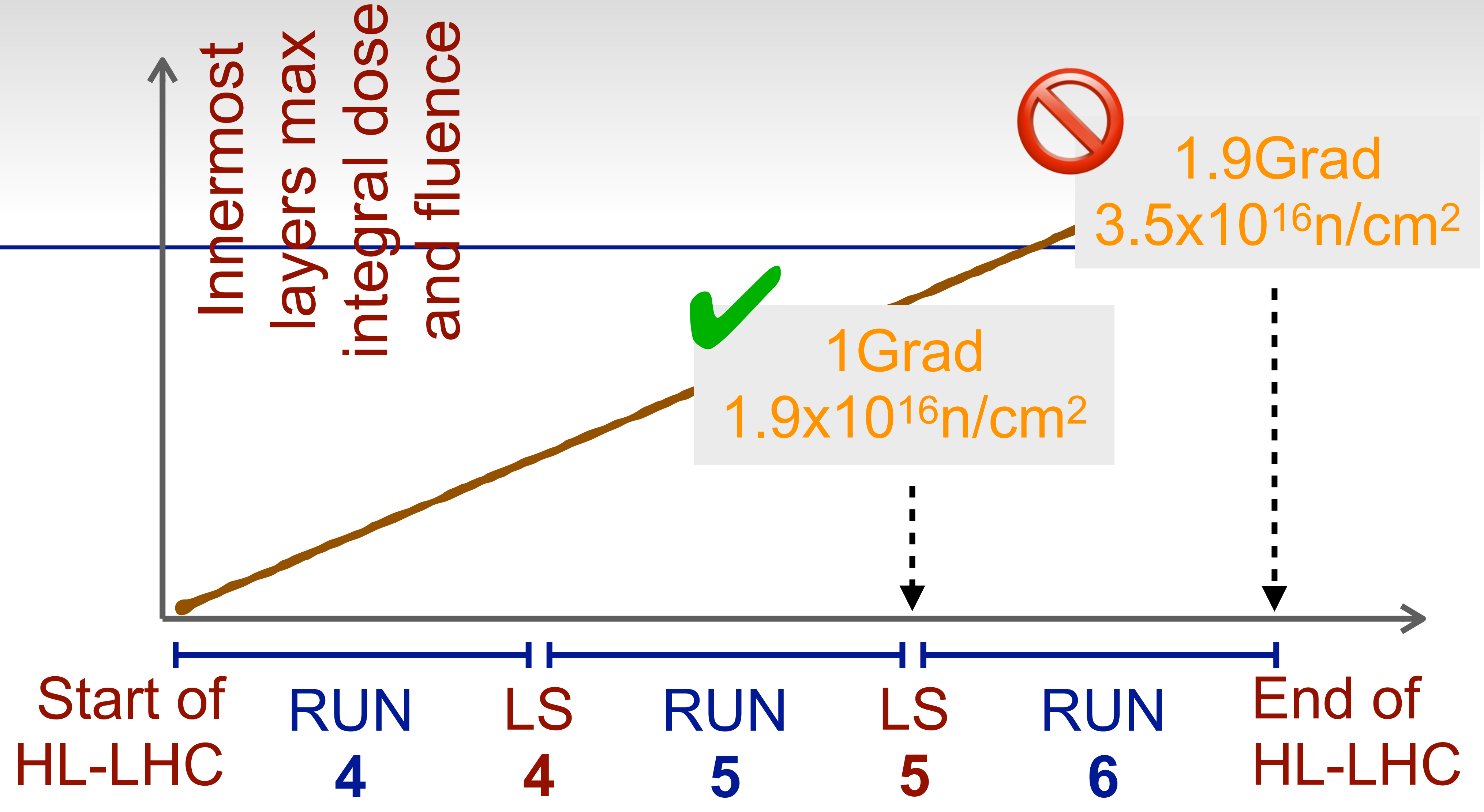
- TEPX - large disks
  - a multi-tool robotic arm pickup and glues the parts arranged onto an appropriate tray beforehand
  - glue deposited by using stamps
  - assembly in batches (6 to 24 modules); up to 3 batches per day possible

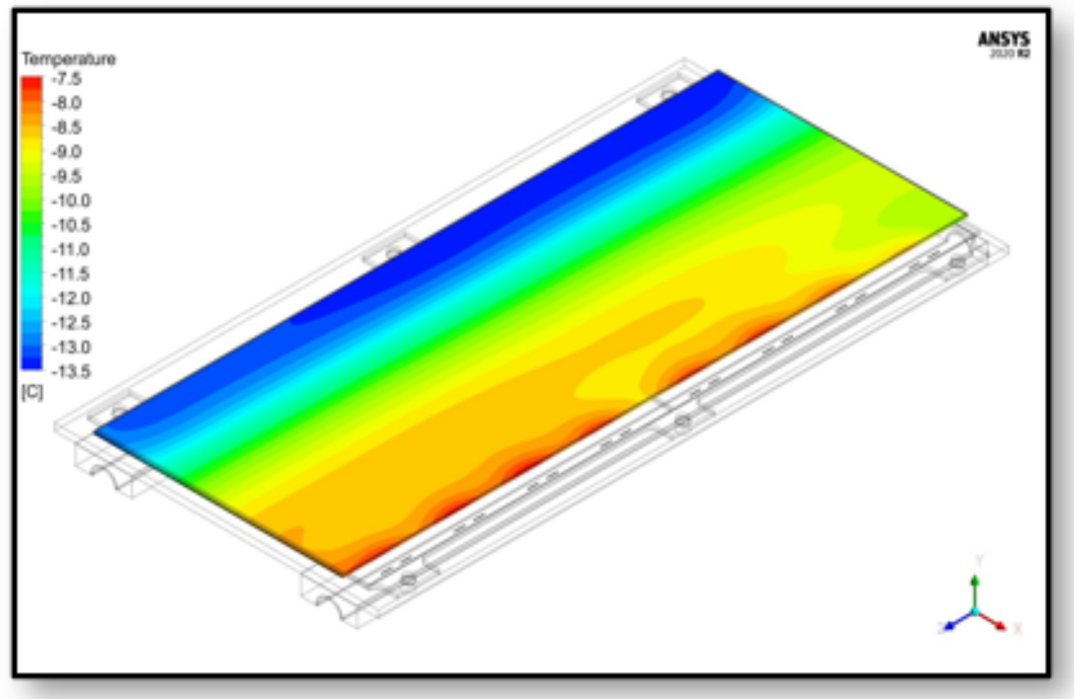


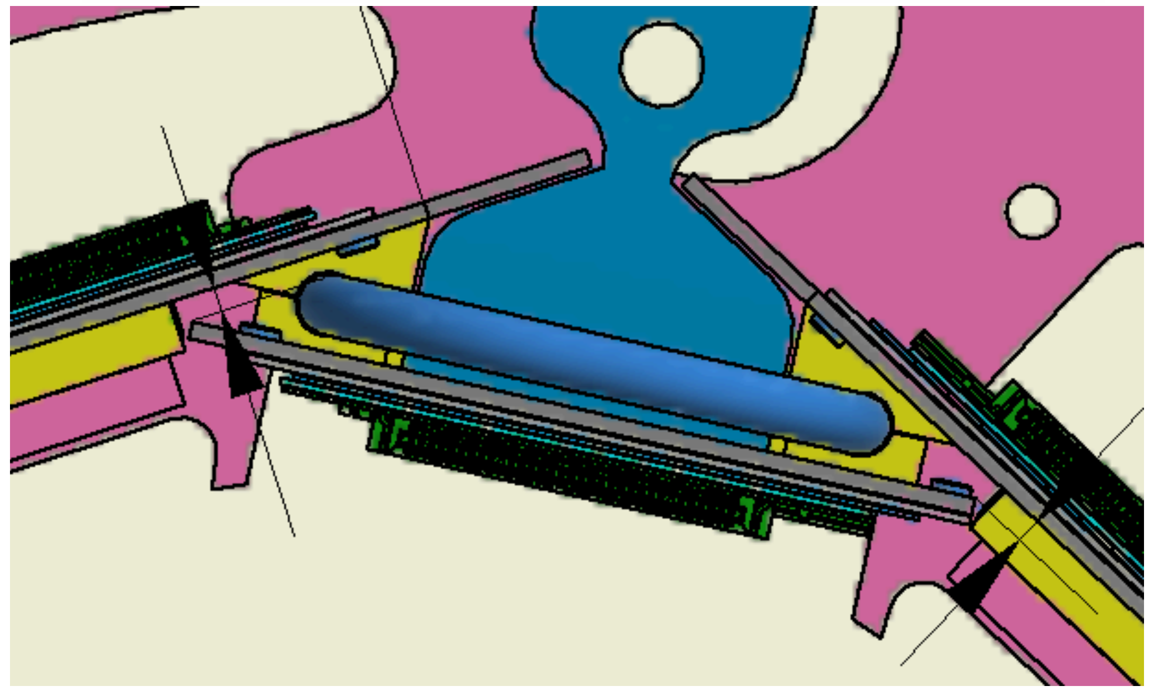
The TEPX robot in PSI with the tool/ parts tray underneath

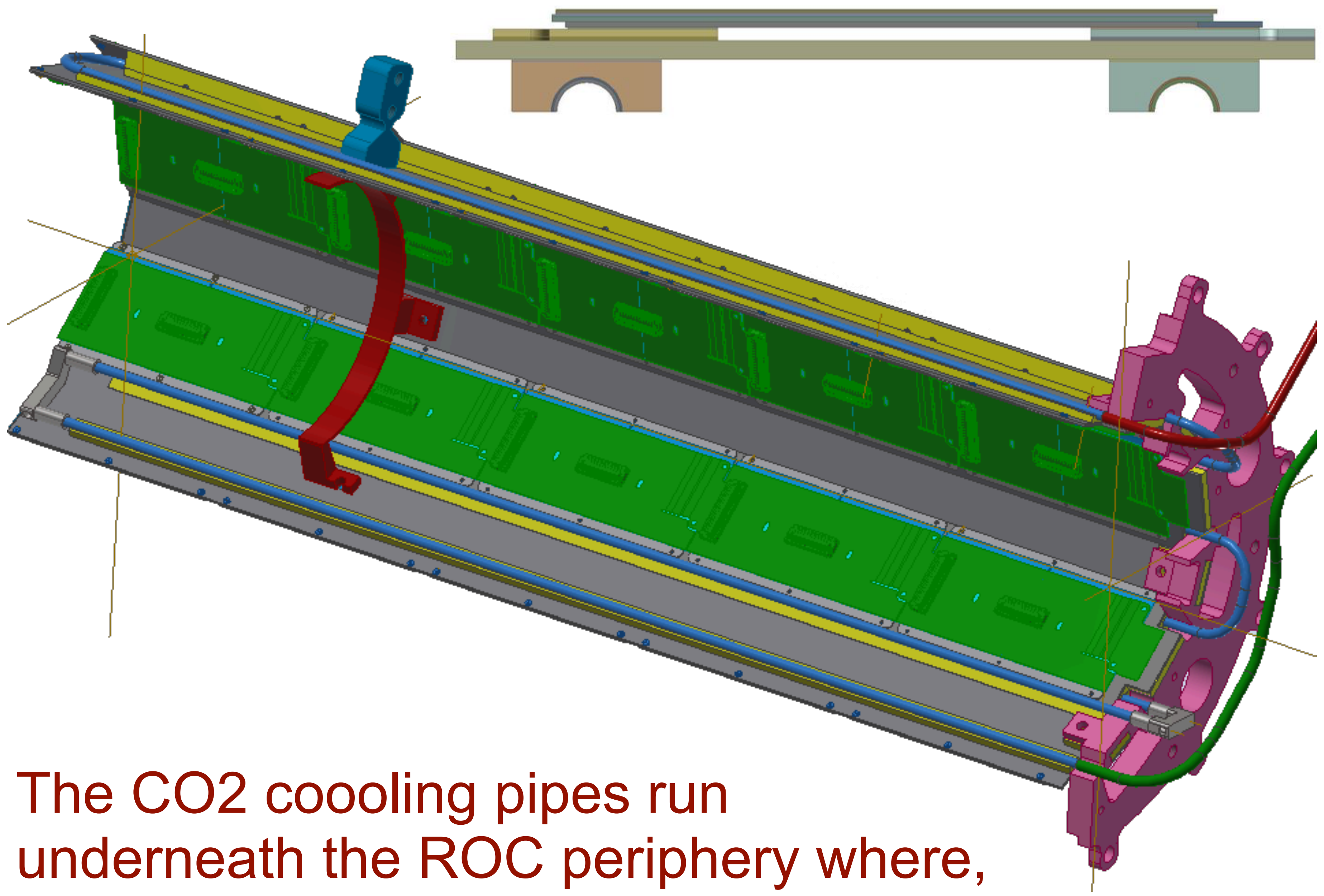
3D choice motivations

- Operating innermost layers/rings until the end of HL-LHC program is not realistic assuming the *ultimate scenario* (4000/fb at the end of the HL-LHC)
  - Replacement of innermost layers/rings in LS5
  - Choice of 3D for barrel layer #1 to ease the L1 modules thermal management despite the accurate optimization of the cooling pipes dimensioning and routing, mechanical supports and interface materials

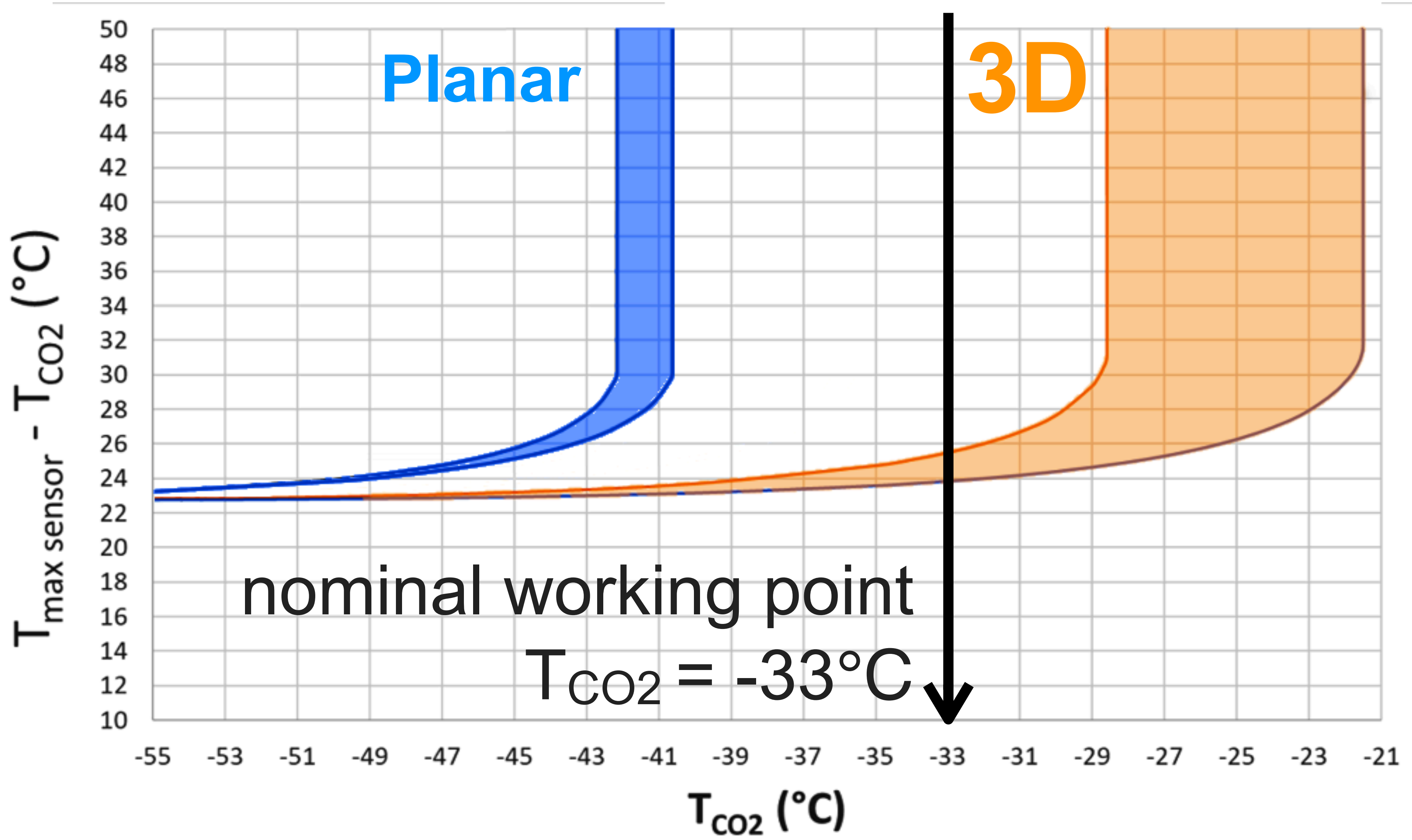






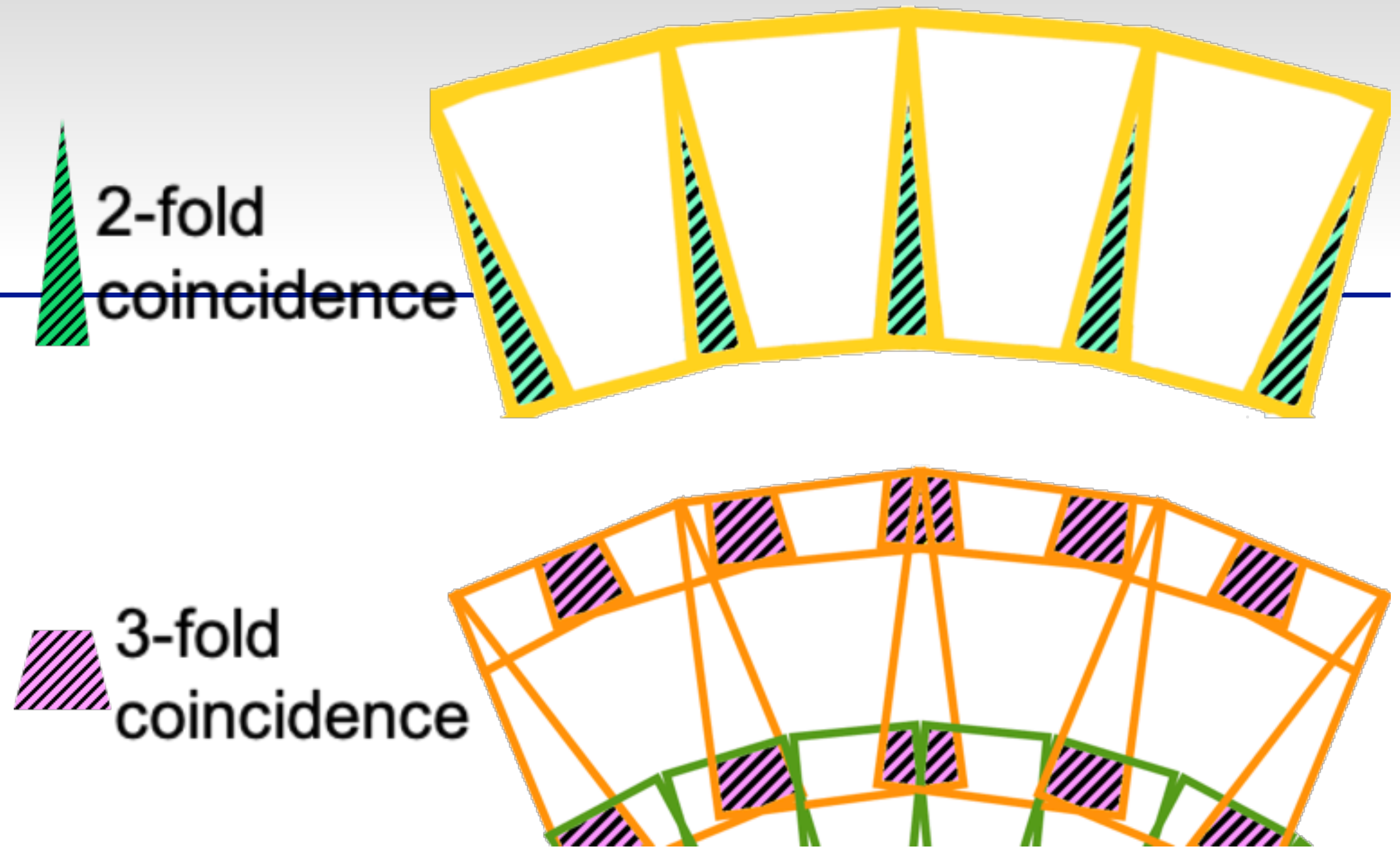


The CO2 coooling pipes run underneath the ROC periphery where, due to the placement of the ShuntLDOs, most of heat dissipation takes place

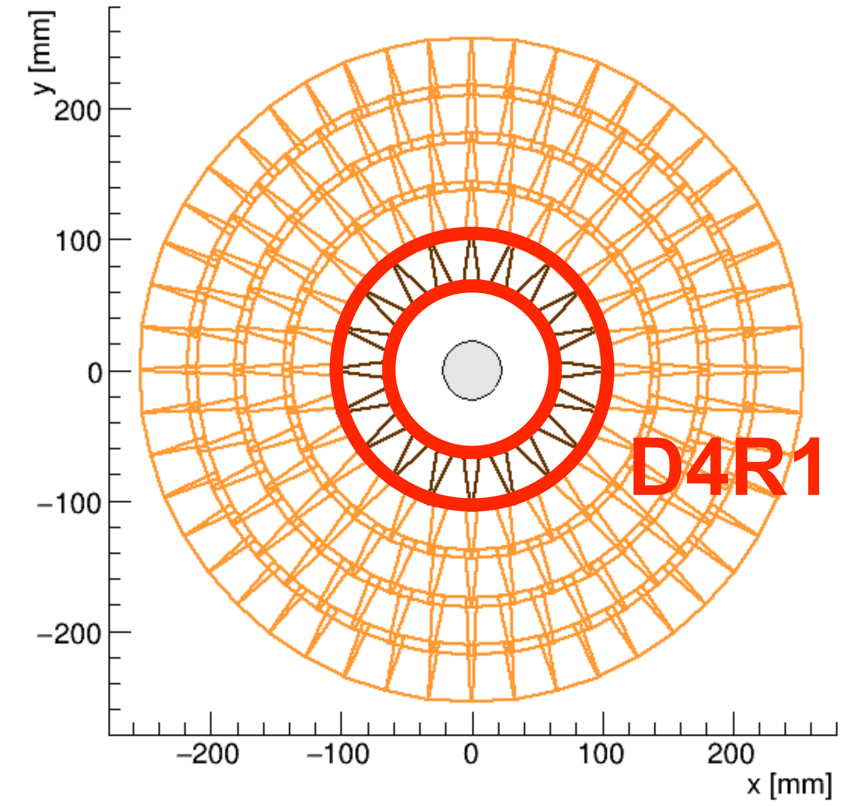


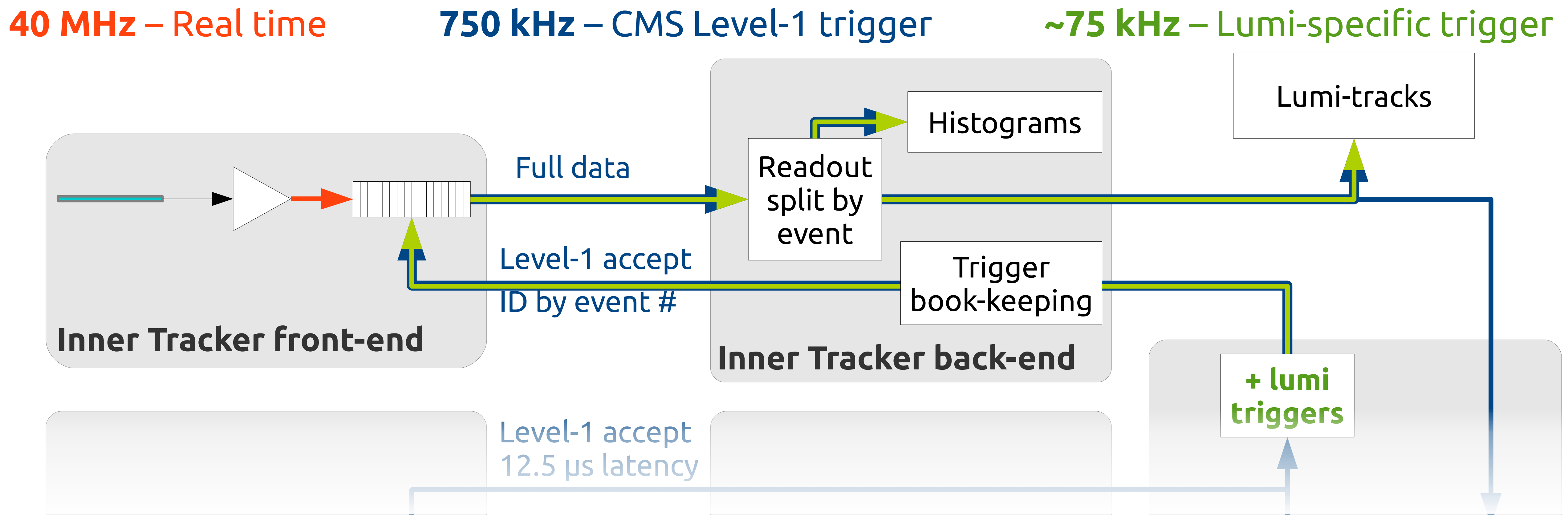
Qualitative behavior of T_{SENSOR} vs. T_{CO2} for L1 planar and 3D modules

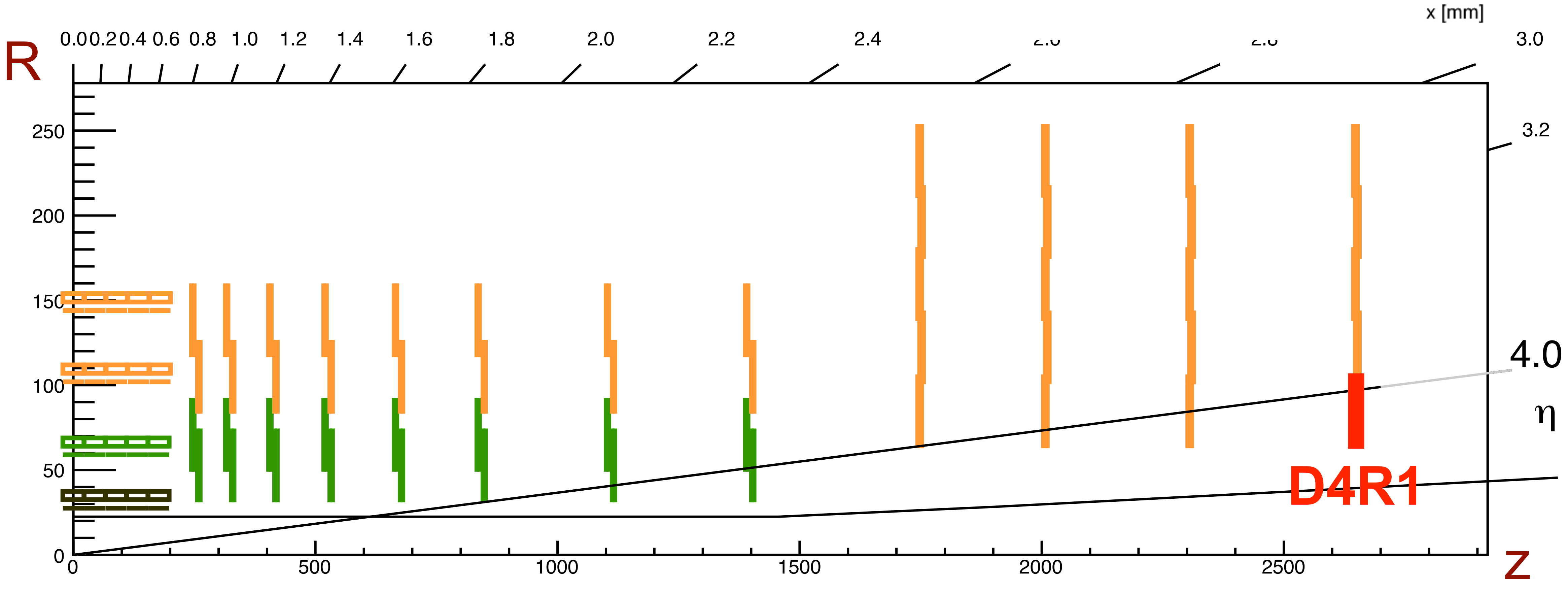
TEPX as luminometer in Phase2



- The Pixel Detector plays a major role in the luminosity measurements in RUN1-3
- **TEPX** (~2m²) devoted also to **luminosity measurements**:
  - operated in **when beams are safe** (ADJUST, STABLE BEAMS) and during VDM scans;
  - requires **dedicated/special DAQ**
    - no data taking: all bandwidth available for lumi triggers (up to ~10MHz);
    - during data taking: special triggers (+10%, 75kHz) added to physics streams.
  - TEPX **D4R1** (outside Tracking acceptance) is **fully dedicated to Beam Radiation Instrumentation and Luminosity** (BRIL) to measure beam background & luminosity during Machine Development and Unsafe Beam Conditions.
  - **Several methods under study for the luminosity measurement** (dedicated lumi processors in the back end): cluster counting; multi-hit stub counting using overlaps; track counting (needs back-end processing)

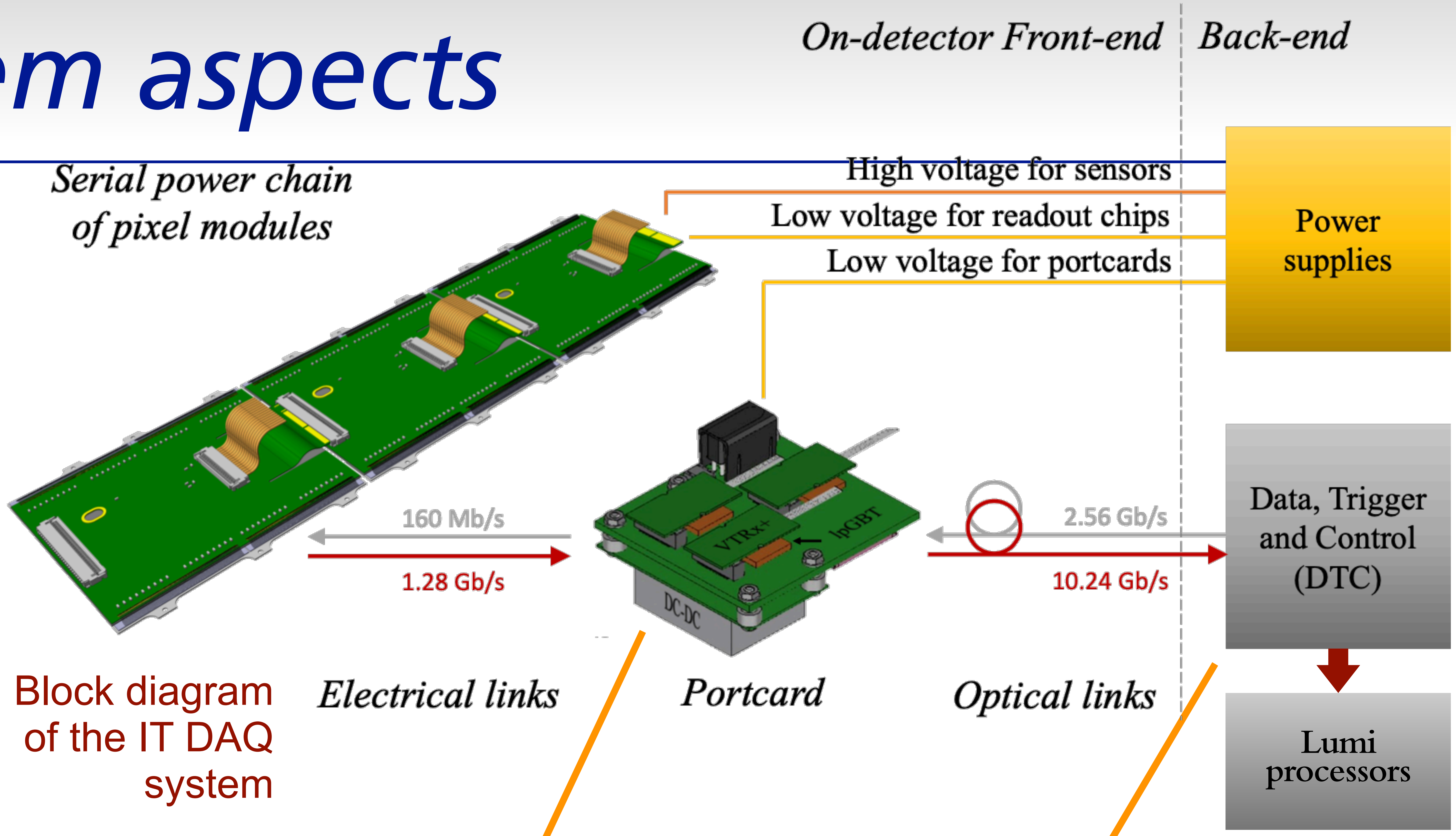




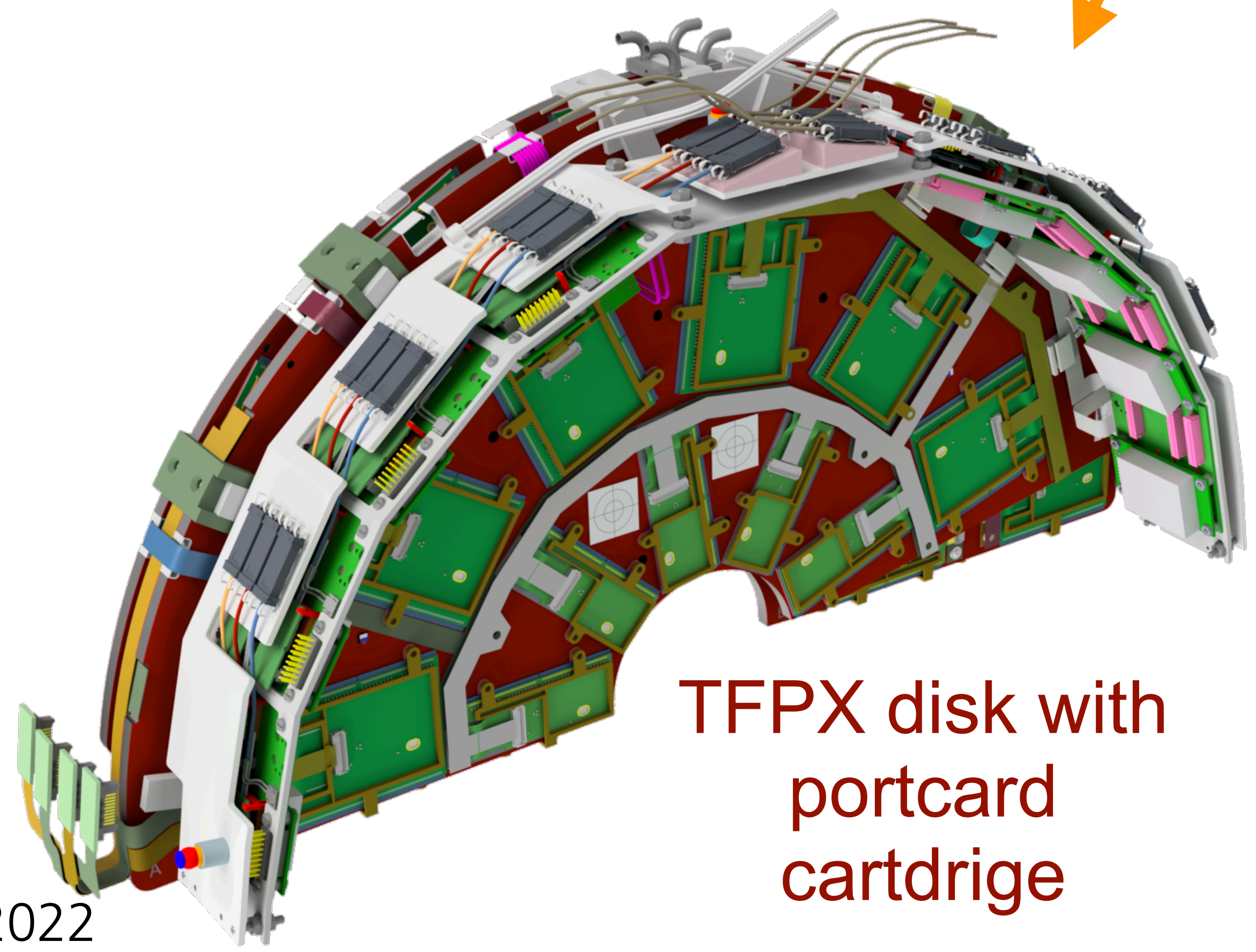


DAQ and other system aspects

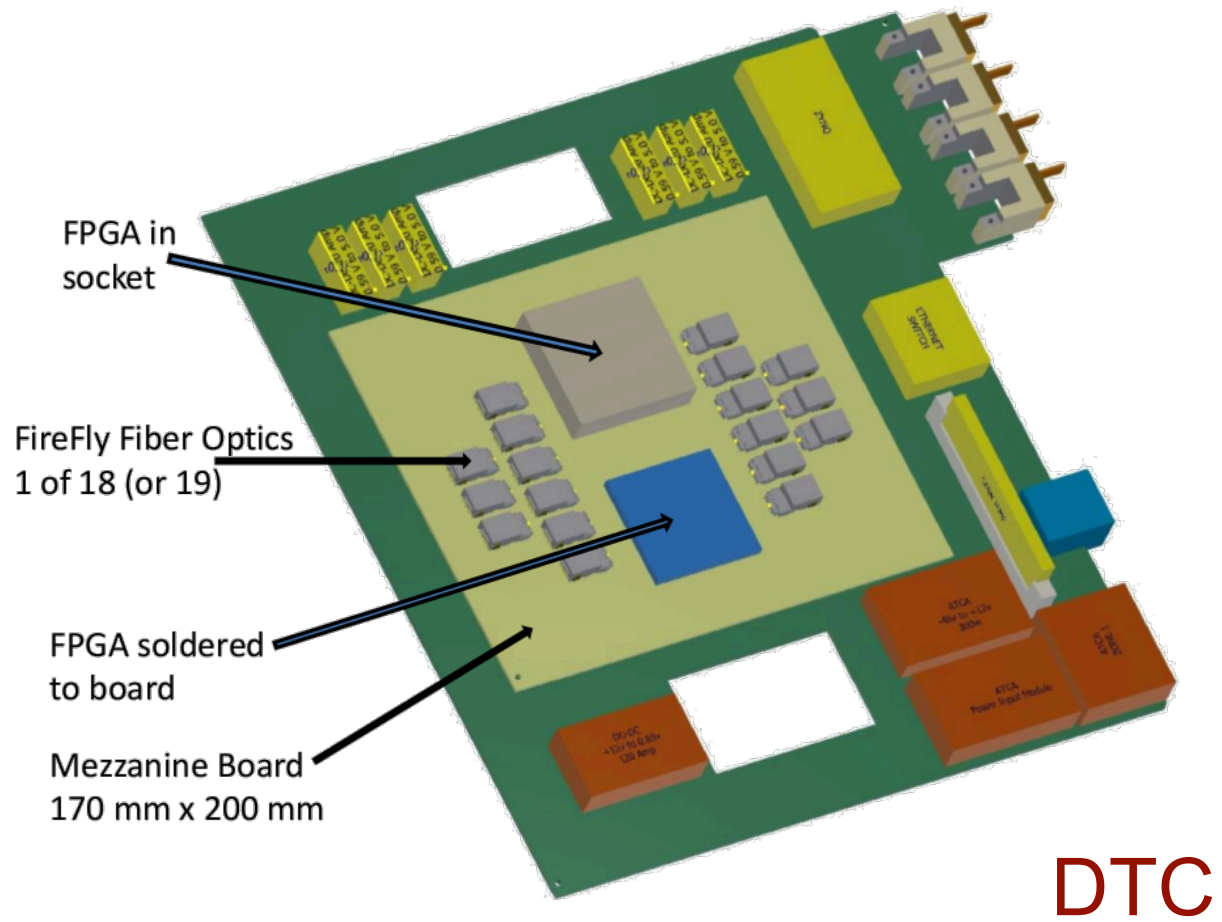
- **Up-links**: data on L1 accept, monitoring info to DAQ and control system
  - Up to 6 electrical up-links @1.28 Gb/s per module to LpGBT
  - Modularity depends on hit rate (location)
  - Efficient data formatting to reduce data rates (factor ~2) / 25% bandwidth headroom on e-link occupancy
- **Down-links**: clock, trigger, commands, configuration data to modules
  - One electrical down-link @160 Mb/s per module from LpGBT
- Communication electronics hosted on 680 dedicated **opto-converter boards** (Portcards)
  - positioned on the IT service cylinder
  - a portcard hosts 3x lpGBTs and VTRx+ links, powered via DCDC converters (1x bPOL12V + 1x bPOL2V5)
- **Back-end electronics**
  - 28 DTC (Data Trigger Control) boards
  - Lumi processors



Block diagram of the IT DAQ system



TFPX disk with portcard cartdrige

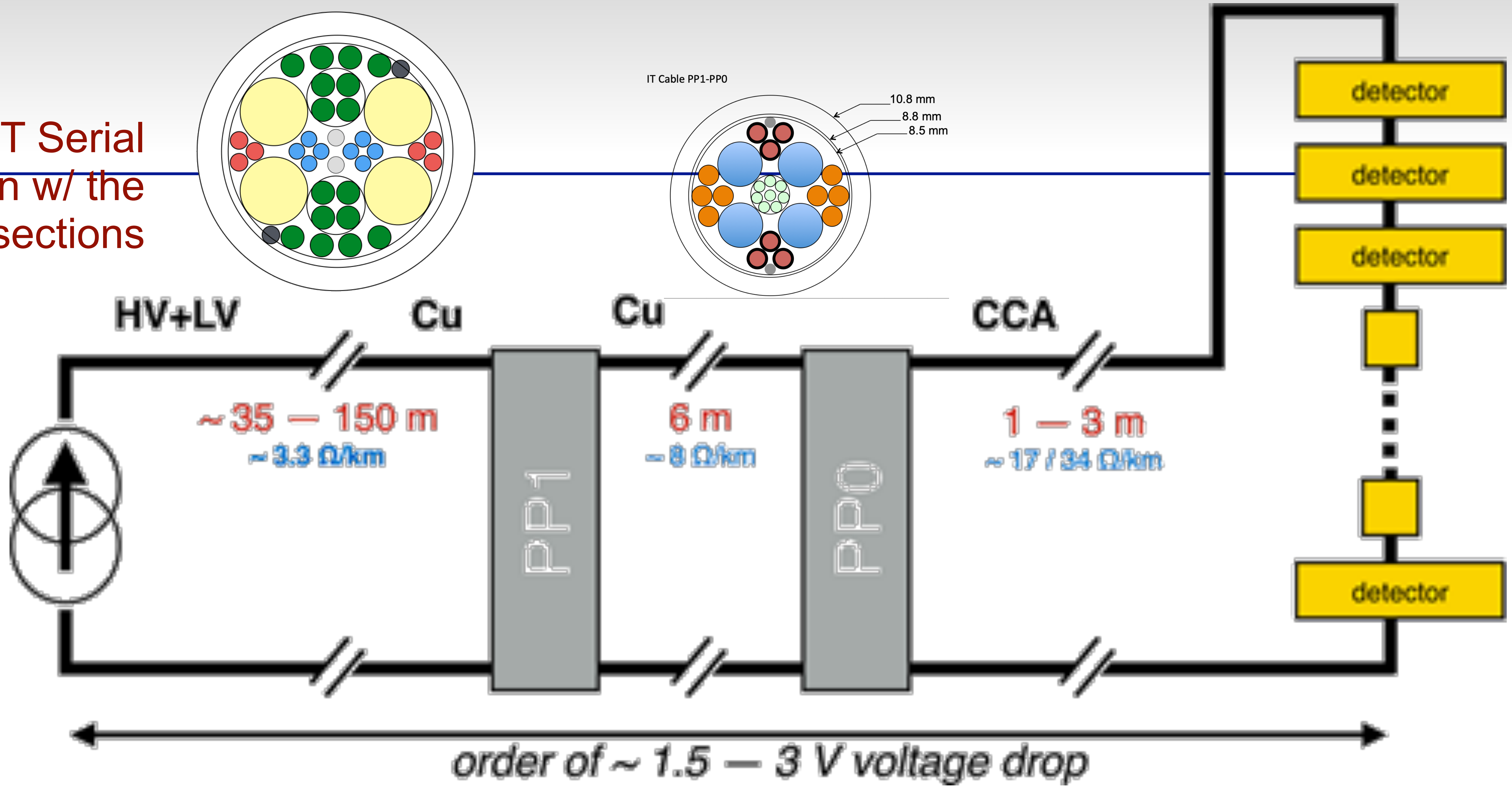


DTC

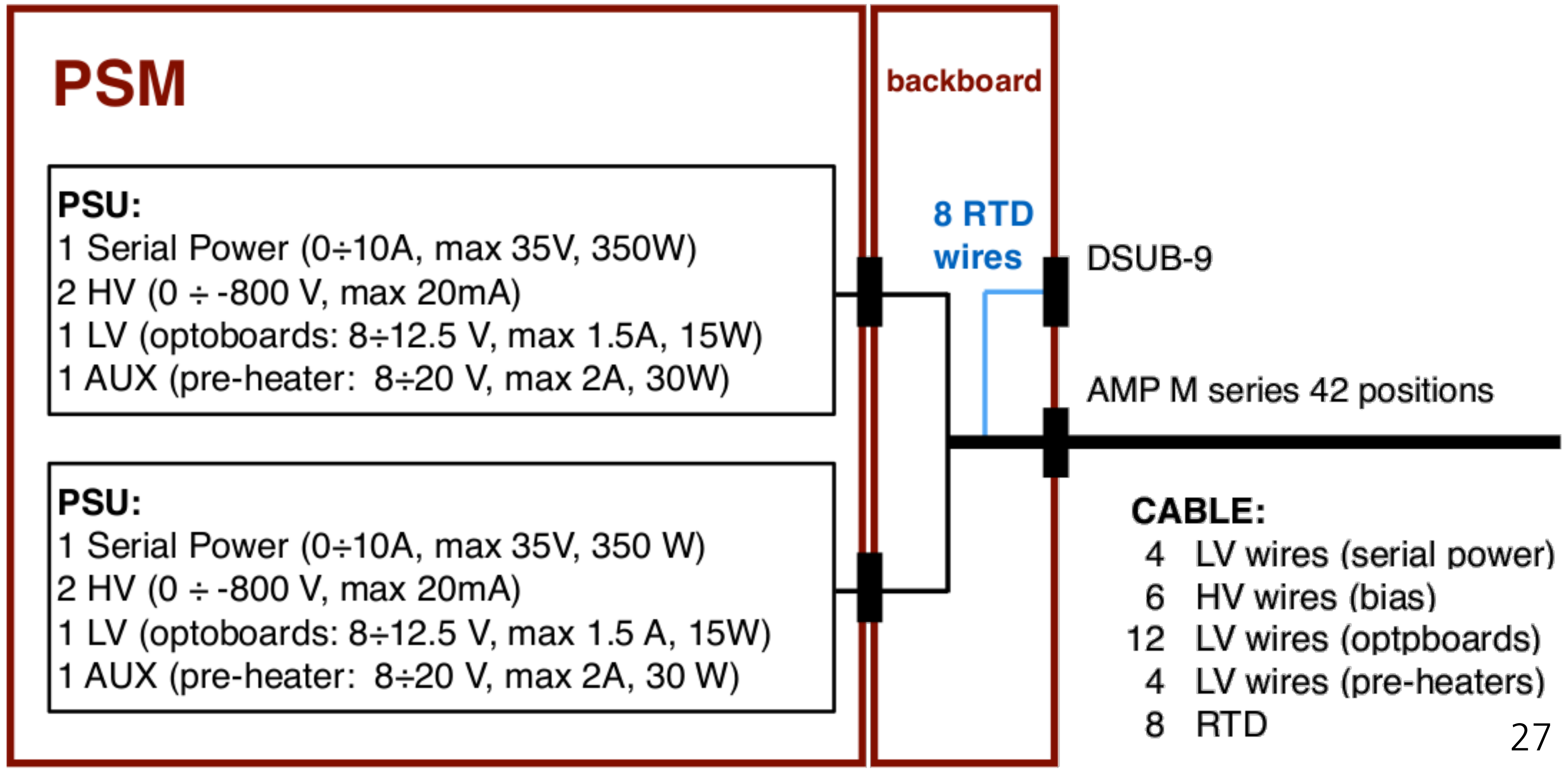
Power system

- >60kW in total
- **Pixel modules SP chains**
  - 500 serial power chains (164 @4A, 336 @8A); 5 to 11 modules/chain
  - High voltage bias is distributed in parallel to modules in each serial chain
- **Optoelectronic services** (680x port cards w/ LpGBT and VTRx):
  - on-board DC/DC converters (parallel powering scheme, similar to OT)
- **Cooling system pre-heaters** (~350)
- Power supply (current sources) system operates inside the CMS experimental cavern
  - stray magnetic field of up to 100mT
  - radiation (considering 10y operation up to 4000/ifb):
    - dose: 5Gy (with dose rates up to $5x10^{-5}$Gy/s)
    - fluence: $3x10^{11}$neq/cm^2 (with rates up to 750 n/cm^2/s)
    - $5.6x10^{10}$ HEH/cm^2 (E>20MeV) (with rates up to 140 HEH/cm^2/s)

Sketch of the IT Serial Power chain w/ the cable cross sections

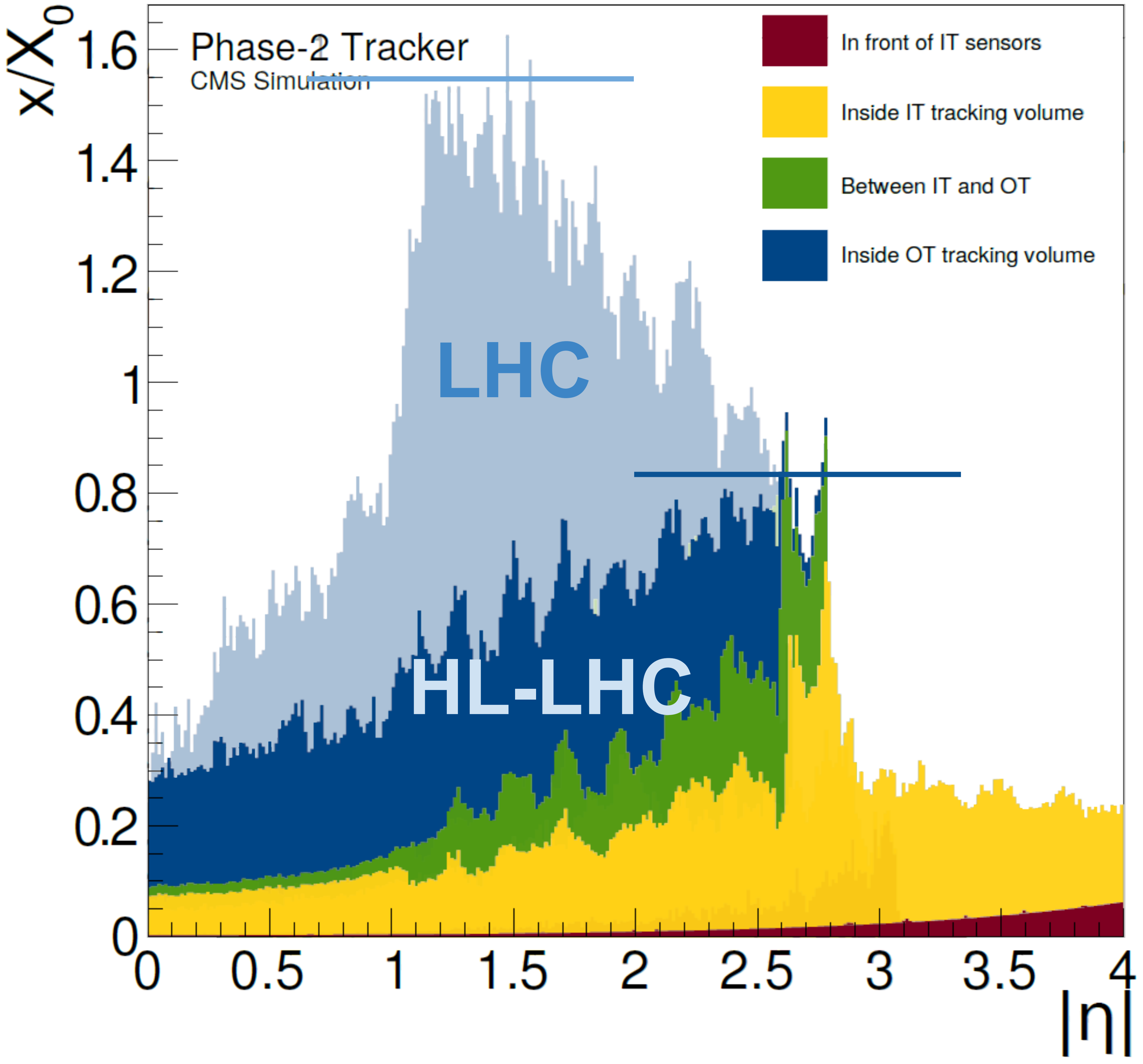


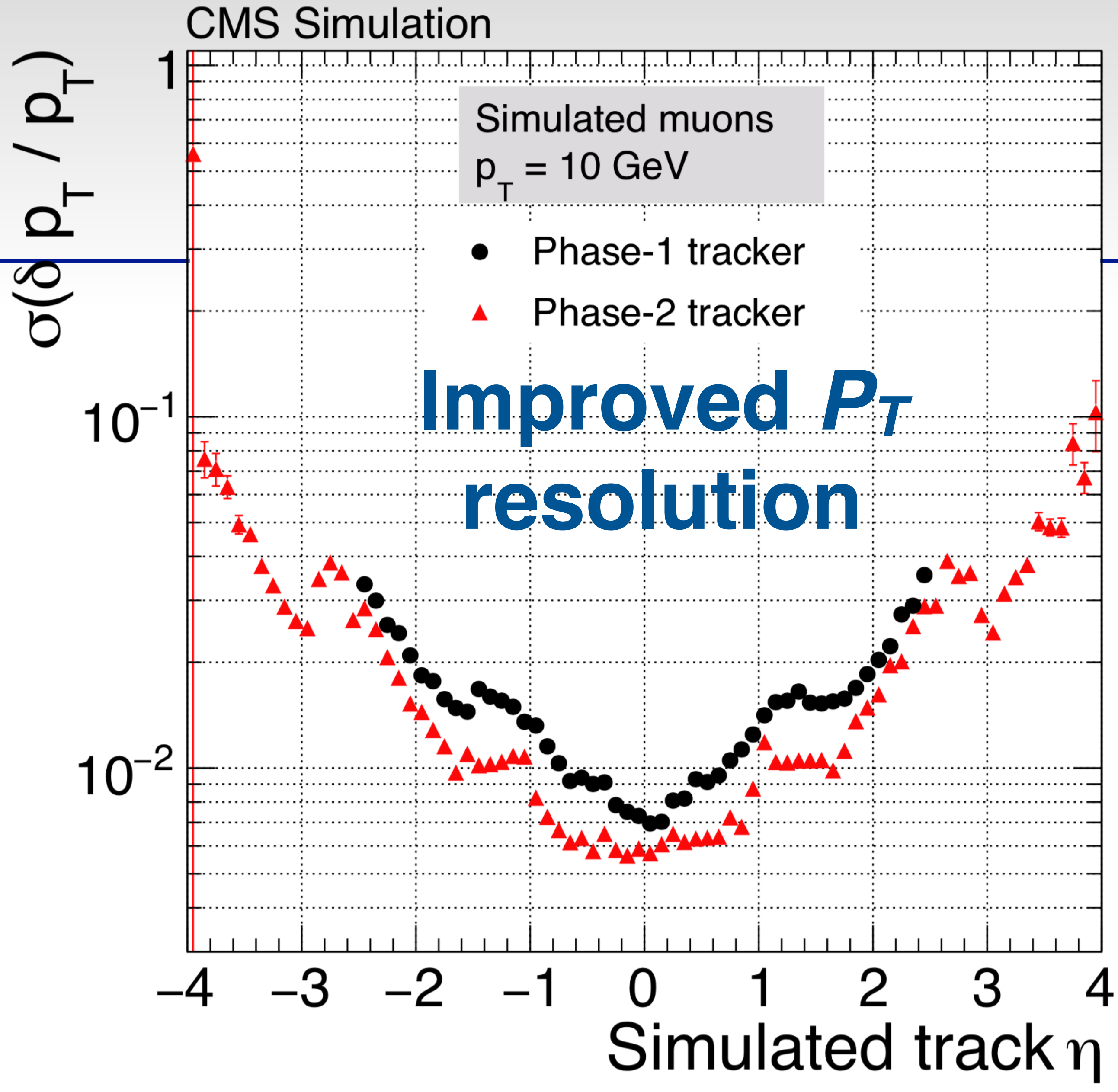
Block diagram of the IT Power Supply Module

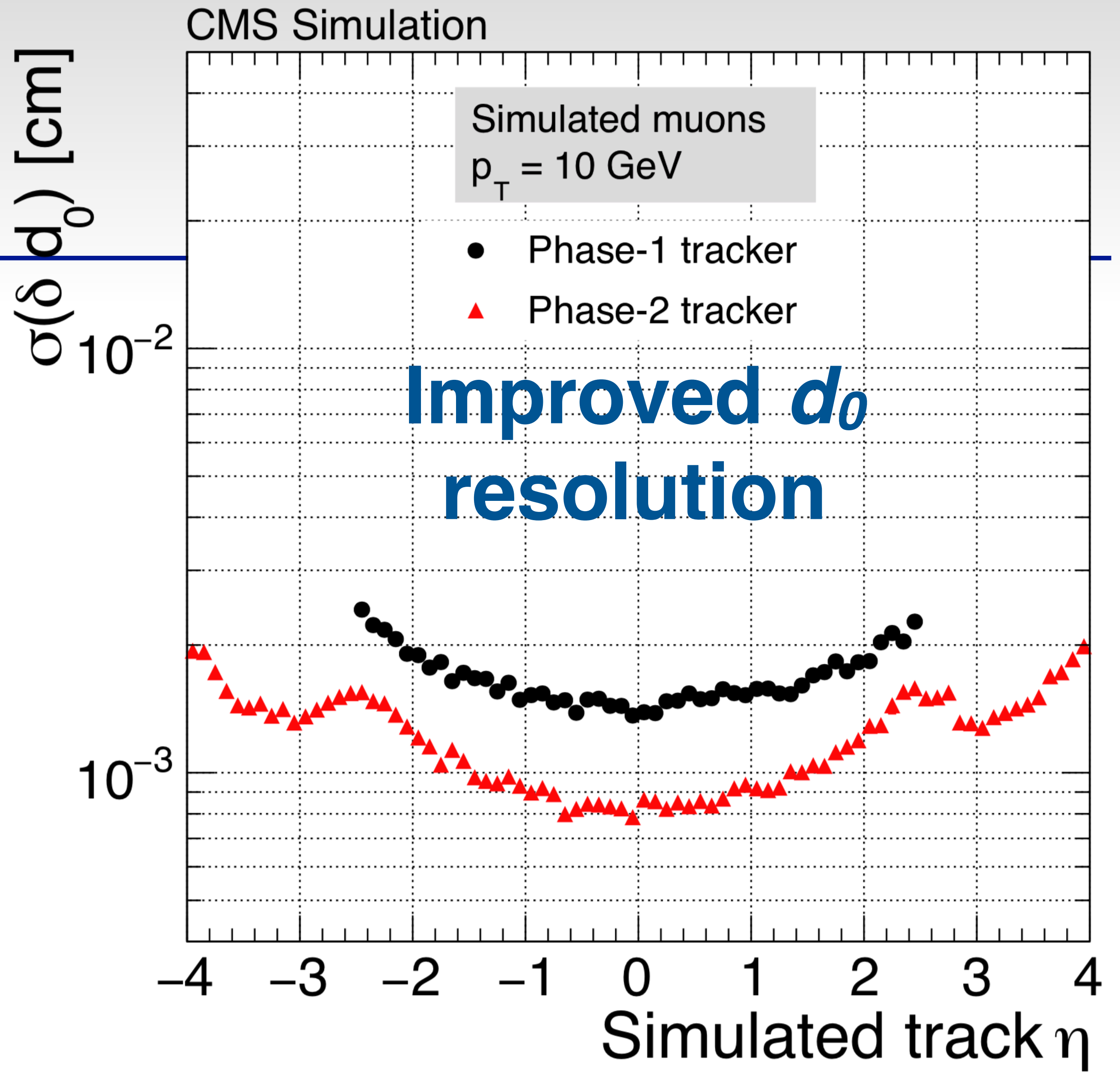


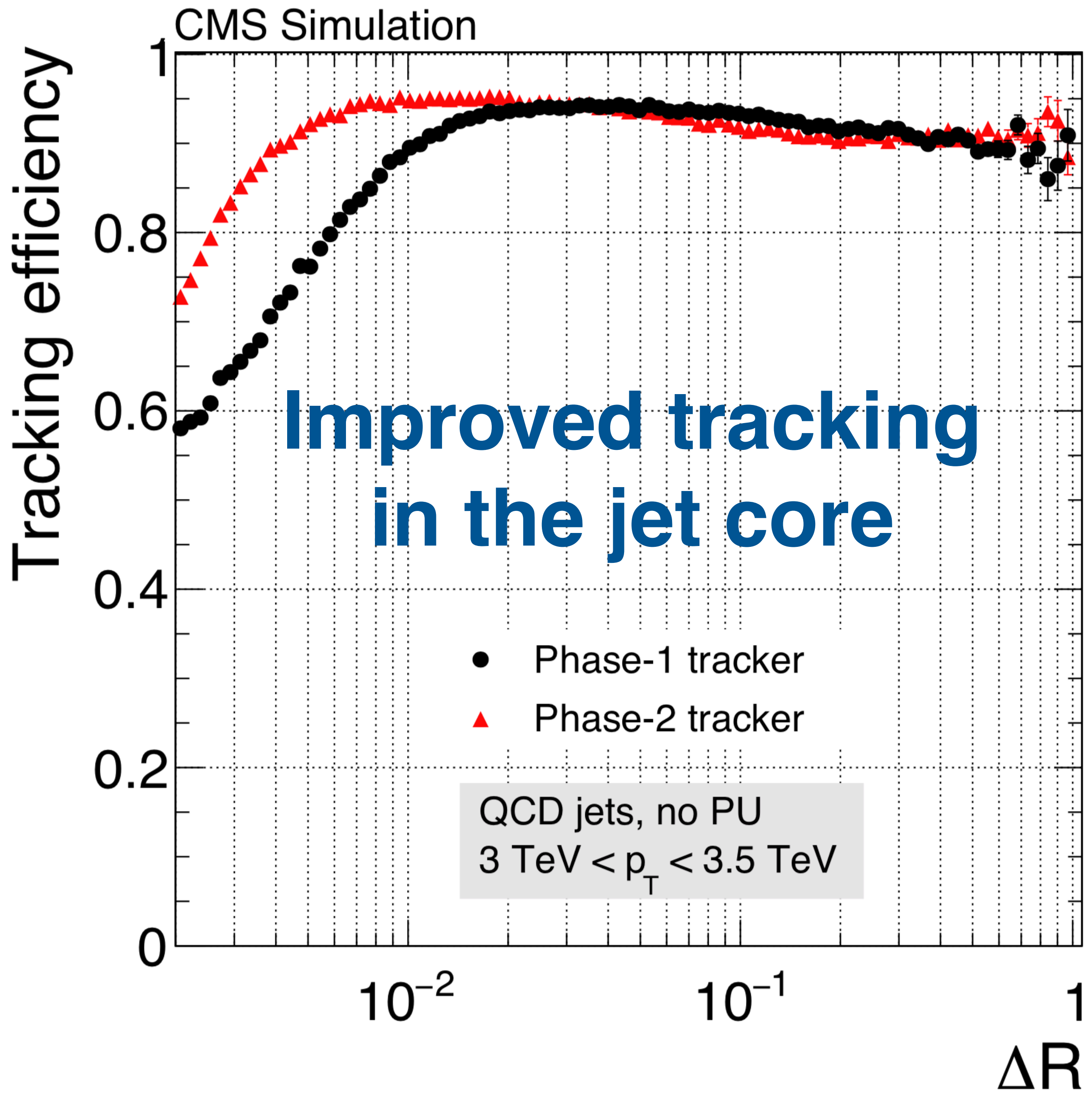
Performance

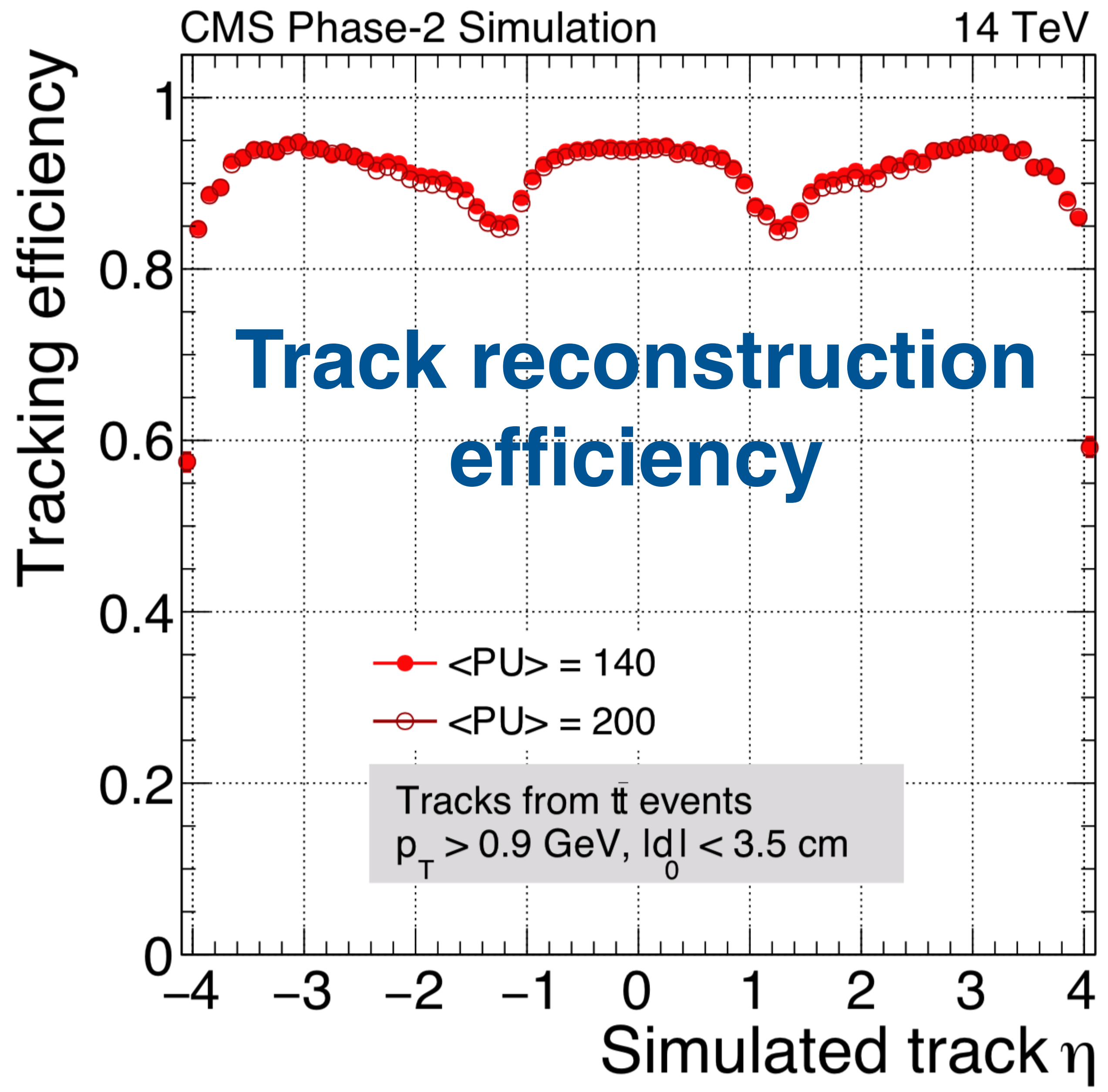
Thanks to the better granularity and the reduced material, the upgraded tracker improves on all physics observables even with 200 PU.
IT is crucial for seeding, the first reconstruction step.











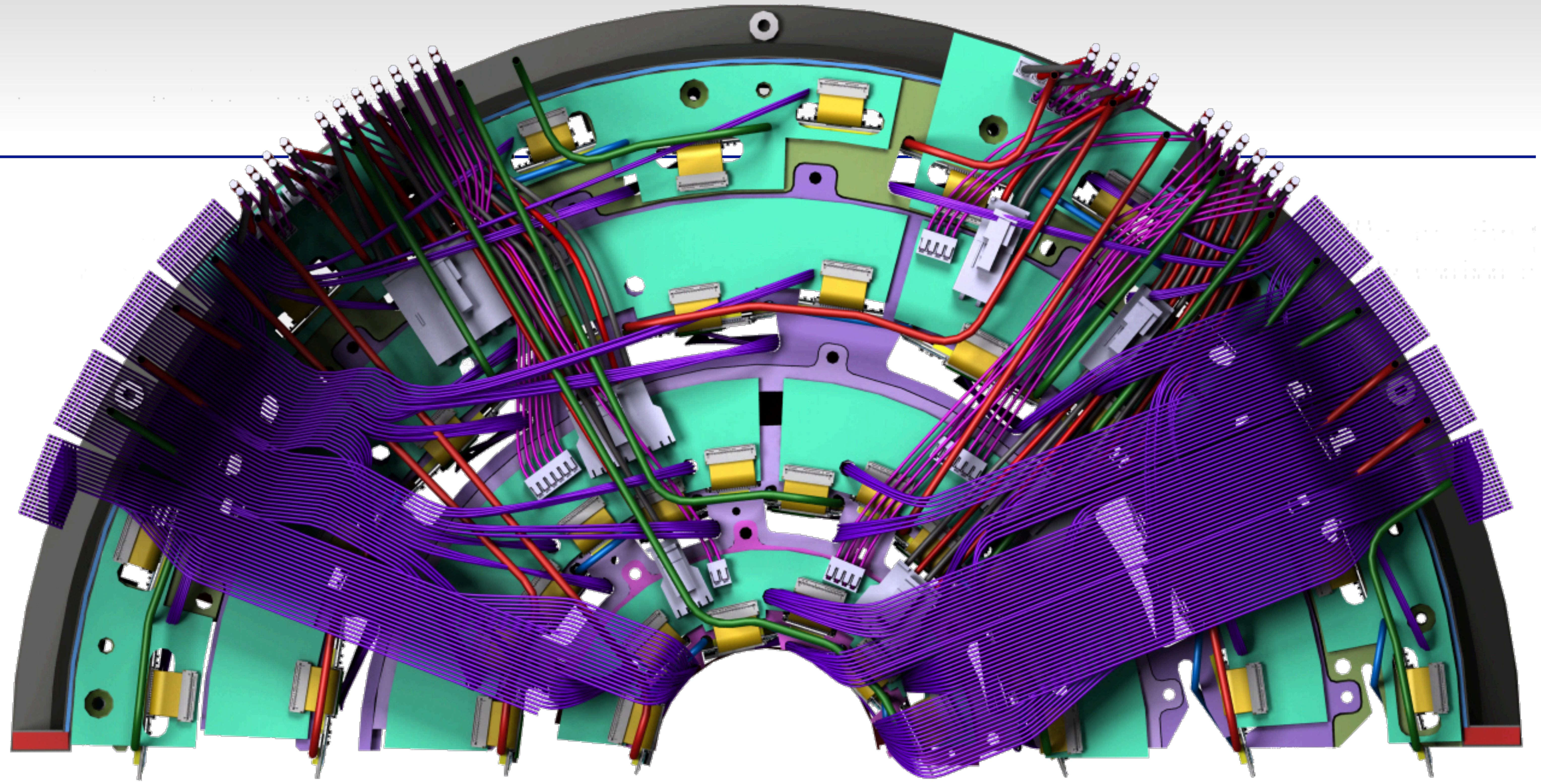
Conclusions

Current Phase-1 pixel detector

~1.8m² Silicon Sensors
123M 100x150μm² pixels
1856 Modules
100kHz max readout rate
15kW power budget

Inner Tracker
(upgraded Pixel Detector)

~4.9m² Pixel Silicon Sensors
~2B 25x100μm² pixels
~4'000 Modules
750kHz readout rate (on L1 accept)
50kW power budget



CAD based study of the services distribution on the TBPX flange

- The CMS Upgrade Inner Tracker is a frontier-technology and extremely challenging project
- The design is finalized or close to finalization in all the main areas (modules, electronics, mechanics, cooling)
- Production and detector integration is ahead of us!

Thank you!