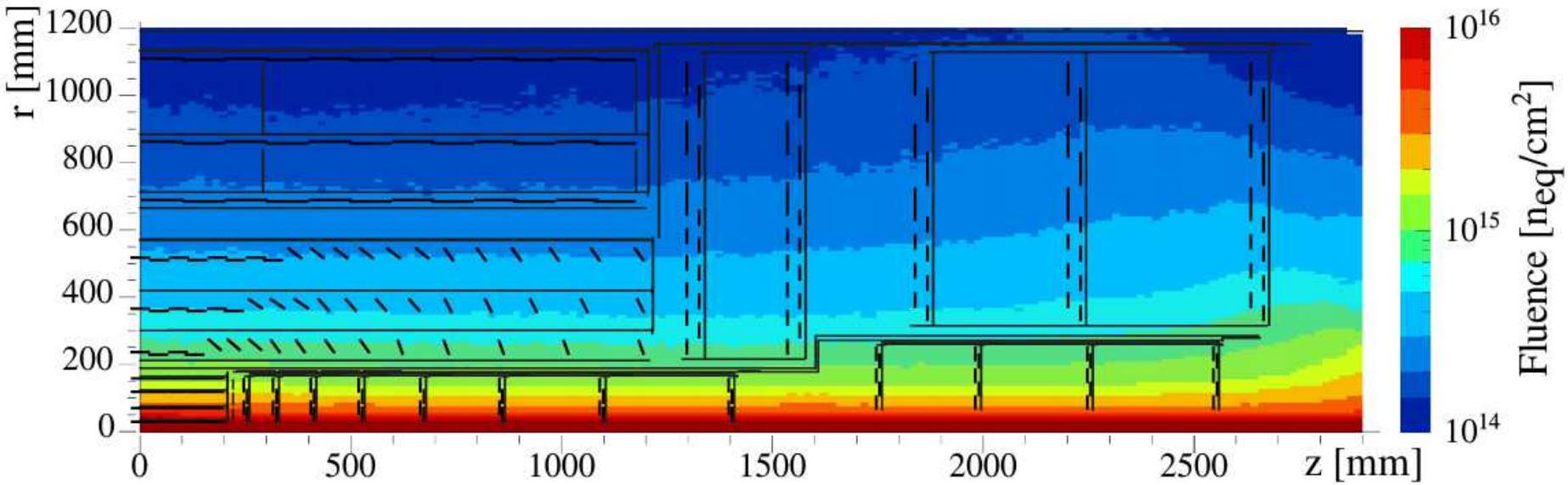
The CMS Tracker Upgrade for the High-Luminosity LHC

E.Migliore
Università di Torino/INFN

on behalf of the CMS Collaboration

The HL-LHC scenario

- Goal: collect 3000/fb (optionally 4000/fb) in about 10 years of operations (2026-2039) with a peak luminosity of 7.5×10^{34} cm^{-2} s^{-1}
  - Increase of $\mathcal{L}_{inst}$ => at 25 ns BX, 200 pileup vertices and O(10^4) tracks per event
  - Increase of $\int \mathcal{L}_{inst} dt$ => unprecedented hostile radiation environment



CMS/FLUKA 3.7.2.0
3000/fb

- Expected fluence up to 2.3×10^{16} 1-MeV n_{eq}/cm^2 or TID 12 MGy

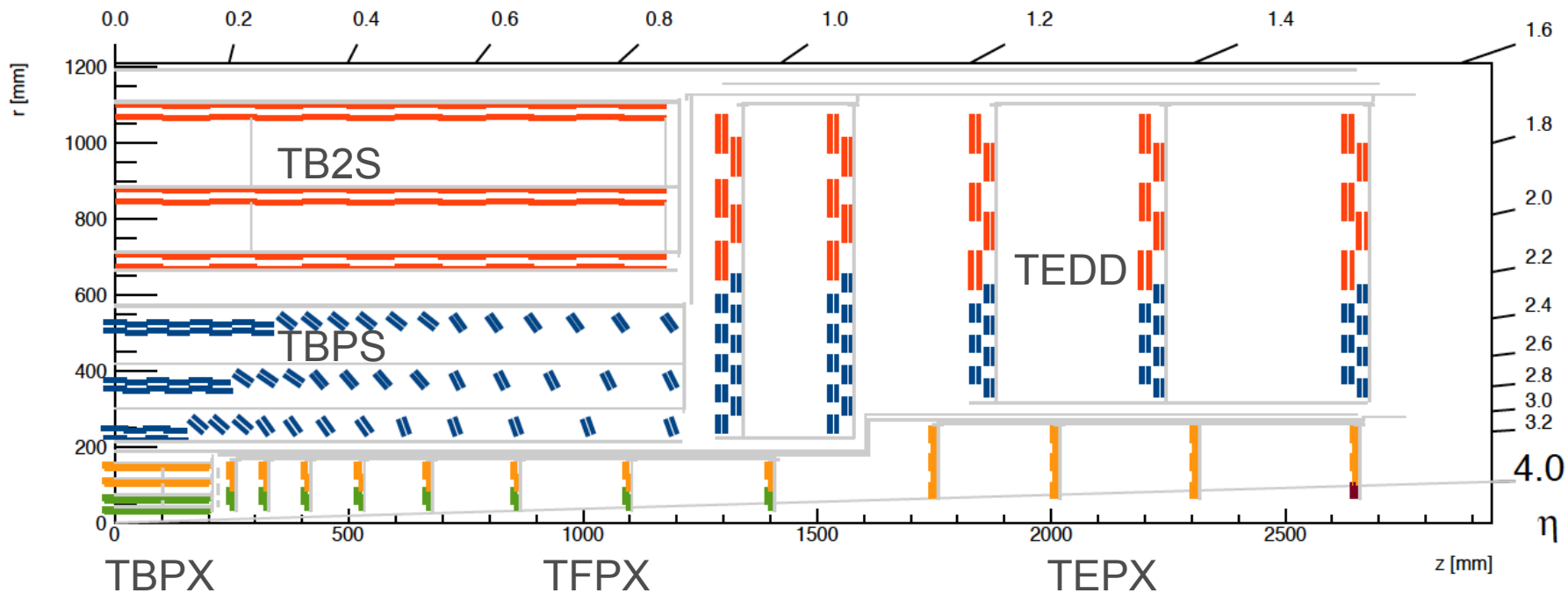
  NB: ≈0.6×10^{14} 1 -MeV n_{eq}/cm^2 fluence as at r=20 cm in current Tracker after 200/fb

Requirements

REQUIREMENT	IMPLEMENTATION
Contribute to L1 trigger	Measure pT>2 GeV tracks at 40 MHz
Compatible with the upgraded CMS L1 trigger • 750 kHz L1 accept trigger rate • 12.5 μs L1 accept latency	Large readout bandwidth and deep front end buffers
Robust two track separation in high energy jet	High granularity • 0.1% occupancy in the Inner Tracker • 1% occupancy in the Outer Tracker
Efficient pileup mitigation	Extended coverage up to $\|\eta\|$~4
Improve tracking performance/momentum resolution measurement	Low material budget
Radiation tolerance up to 3000/fb	• Operations at -20 °C • Rad-hard sensors and ASIC • Option of replacing the innermost layer of barrel pixel at half the nominal dose

The CMS Tracker for HL-LHC

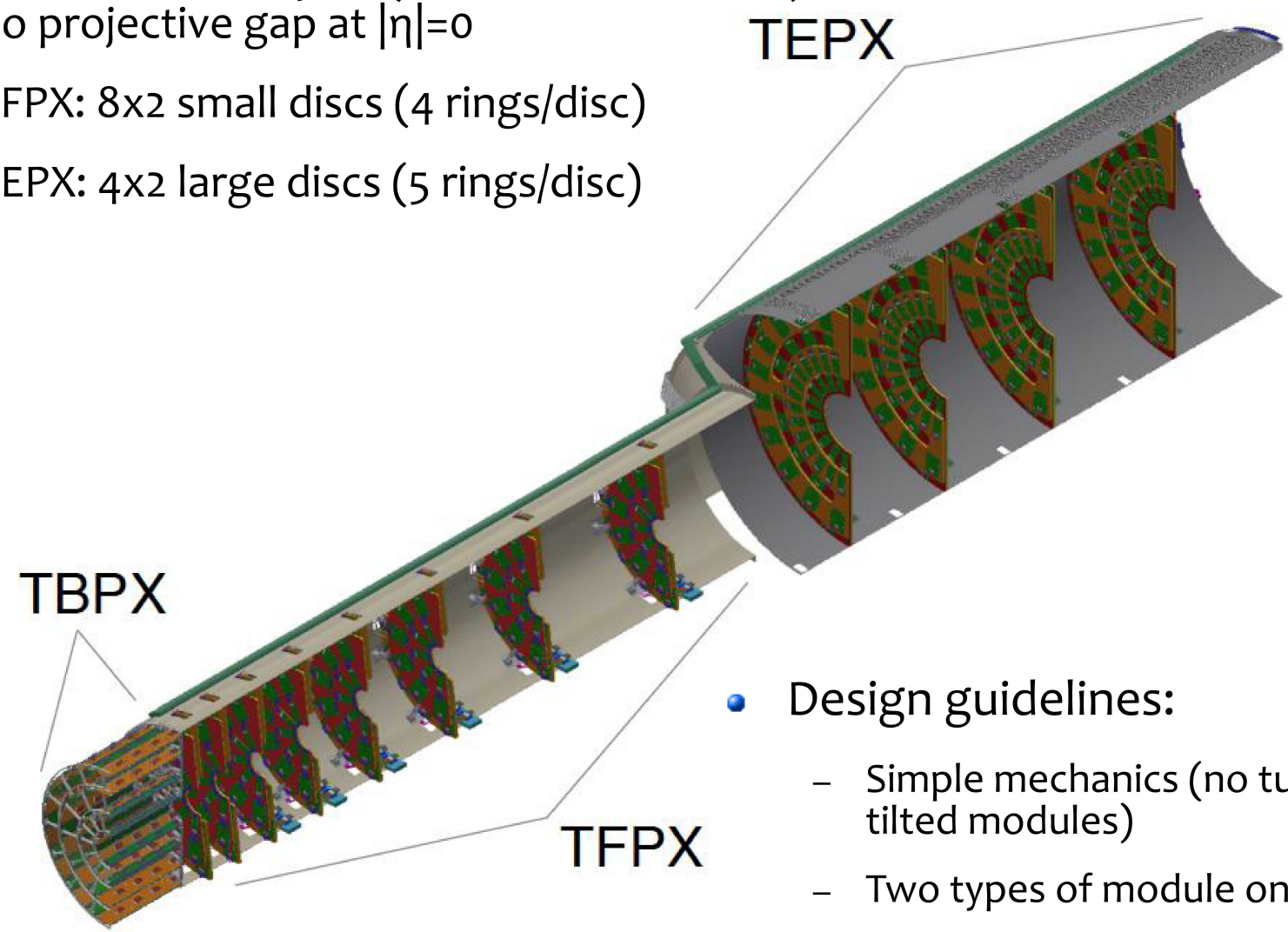
- Outer Tracker: main detector for retaining the L1 trigger thresholds low enough to be fully efficient for the electroweak physics
  - PS: (macro)pixel-strip modules
  - 2S: strip-strip modules



- Inner Tracker: main detector for pattern recognition
  - 1x2 chip (hybrid)pixel modules
  - 2x2 chip (hybrid)pixel modules

Inner Tracker

- TBPX: 4 barrel layers (4+5 modules/ladder) no projective gap at |η|=0
- TFPX: 8x2 small discs (4 rings/disc)
- TEPX: 4x2 large discs (5 rings/disc)

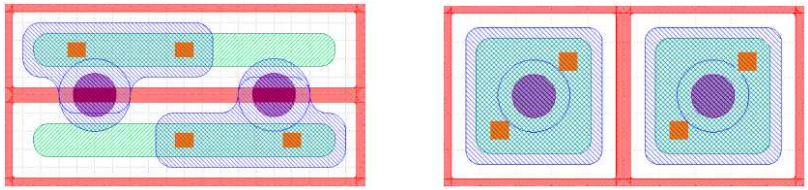


- Design guidelines:
  - Simple mechanics (no turbines or tilted modules)
  - Two types of module only: 1x2 or 2x2 chips
  - Fully accessible for maintenance and repair
- Silicon surface 4.9 m^2 and $2x10^9$ channels

IT sensors

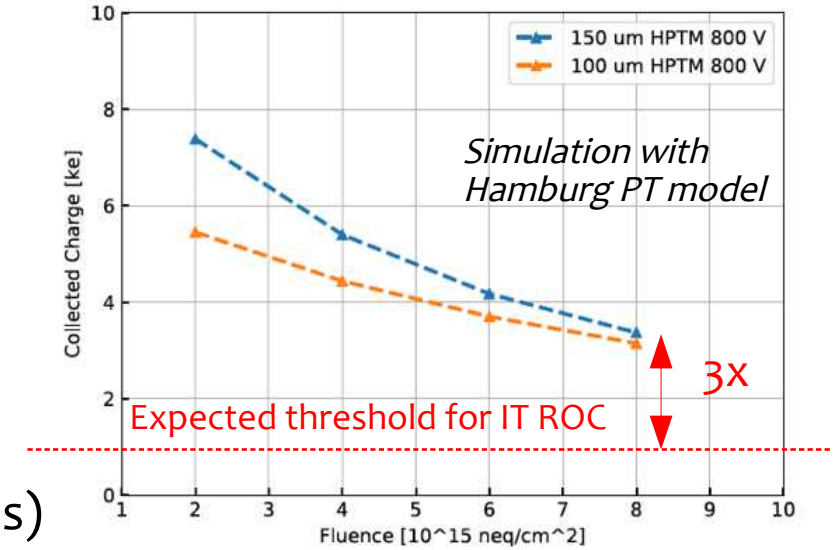
- Small pixel cells (1/6 of the pixel cell of the current CMS pixel detector) with two possible aspect ratios (25x100 μm² and 50x50 μm²) both compatible with the same bond pad pattern

25x100 μm² (baseline) 50x50 μm²



- Technology:
  - Planar n-in-p sensors (baseline)

    Efficient charge collection after irradiation
    - Thin (100-150 μm active thickness)
    - High bias (800-1000V) => spark protection between the ROC and the sensor

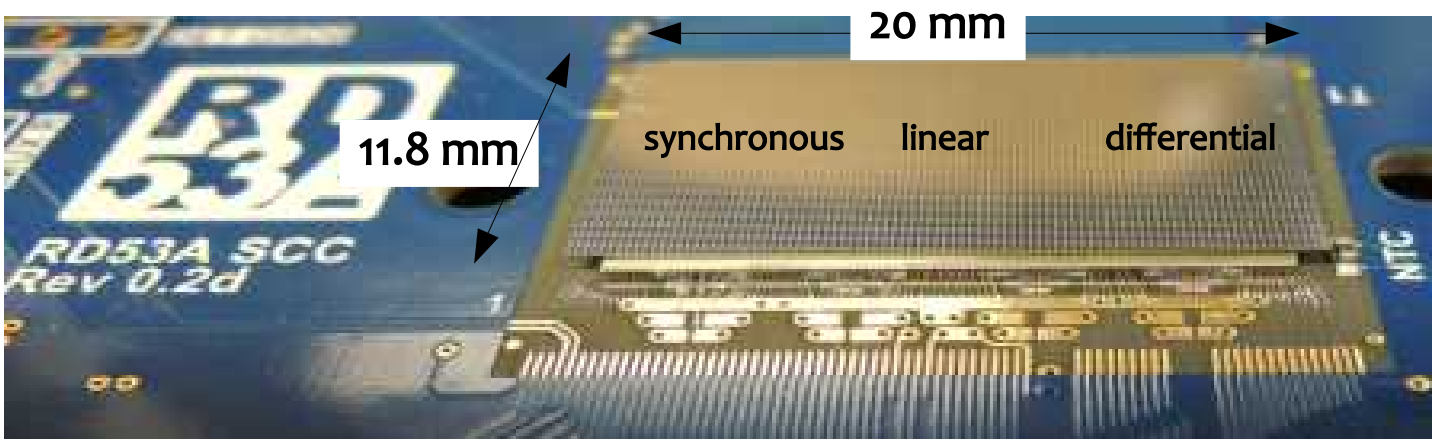


  - 3D sensors (option for the innermost modules)
    - Low bias (150 V) required for efficient charge collection after irradiation
    - Larger cell capacitance (up to 50 fF)

- Final choice on cell aspect ratio and sensor technology still to be taken

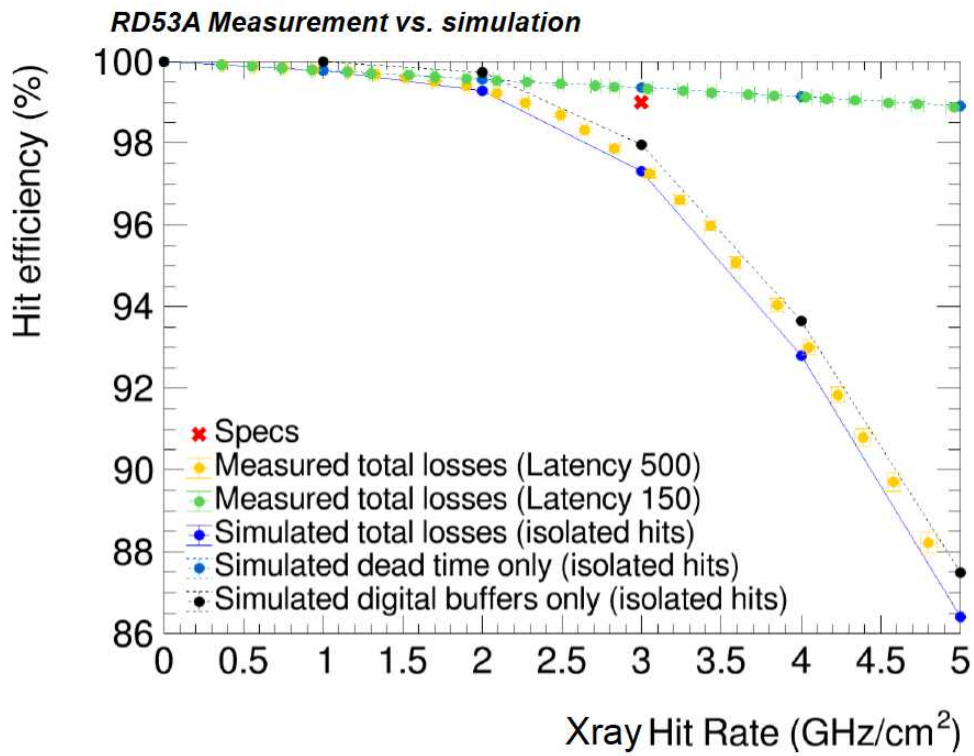
IT readout chip

- ROC developed by CERN/RD53 collaboration
  - Radiation tolerant (TID 12 MGy)
  - High hit (3.2 GHz/cm^2) and trigger rate (4x1.28 Gb/s output links)
  - Low threshold (1000e)
- First prototype (RD53A) delivered in 2018 for qualification
  - ½ size of the final chip
  - 3 different architectures for the analog FE, all working
  - Fully functional after 5 MGy



IT ROC on a test bench

- Hit rate capability measured in the lab with an X-ray source (isolated hits)



Measured hit losses at 3.75 µs latency (dead time)

Measured hit losses at 12.5 µs latency (digital buffer overflow)

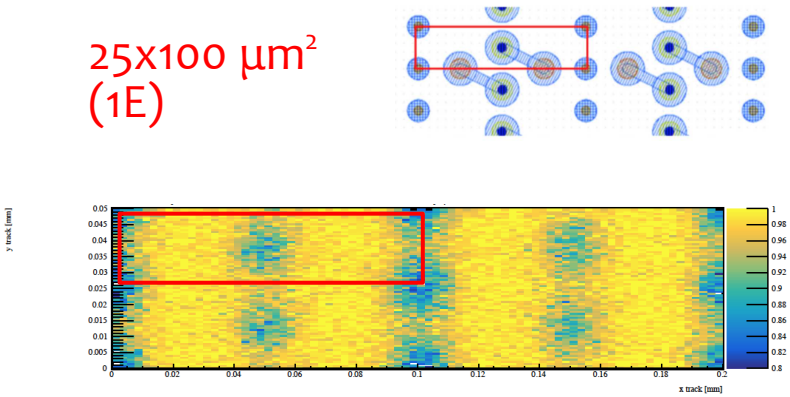
- Simulation reproduces the separate contributions of hit losses due to the digital buffer and to the dead time
- ROC expected to meet the design specs (99% efficiency at 3.5 GHz/cm^2) with clustered hits

IT single ROC+sensor assemblies

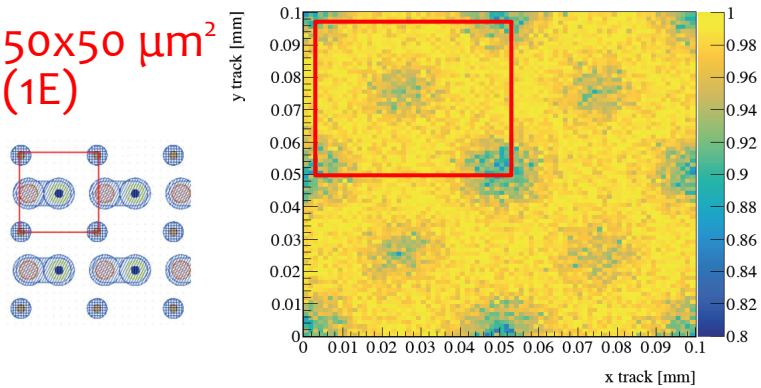
- Intense beam-test campaign on RD53A+irradiated sensor assemblies
- Example of results: efficiency maps for
  - 3D sensors (FBK, 130 µm thickness) irradiated up to $1x10^{16}$ 1-MeV n_{eq}/cm^2
  - beam test at CERN H6, 120 GeV proton beam at normal incidence

after irradiation
normal incidence

25x100 µm² (1E)



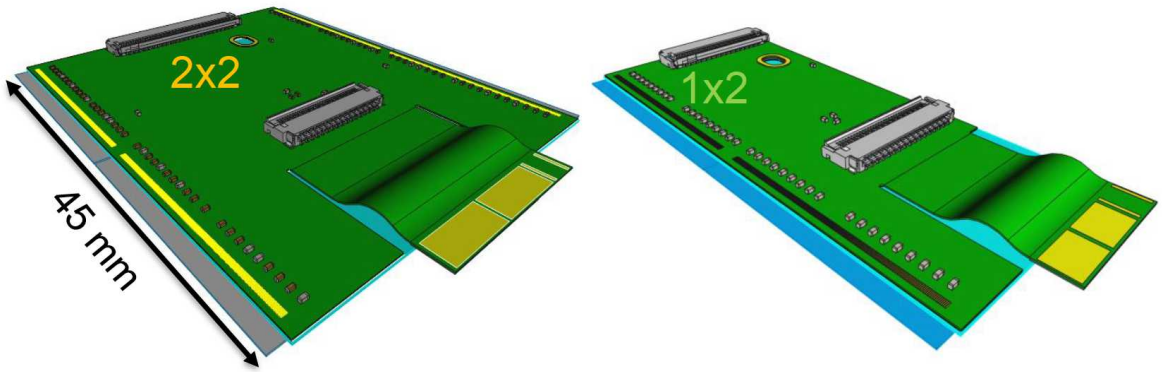
50x50 µm² (1E)



	25x100 um²	50x50 um²
Before irradiation	97.3 % (HV=3 V)	98.6% (HV=15 V)
After irradiation target fluence $1x10^{16}$ 1-MeV n_{eq}/cm^2	96.6% (HV=120 V)	97.5% (HV=150 V)

IT modules and powering scheme

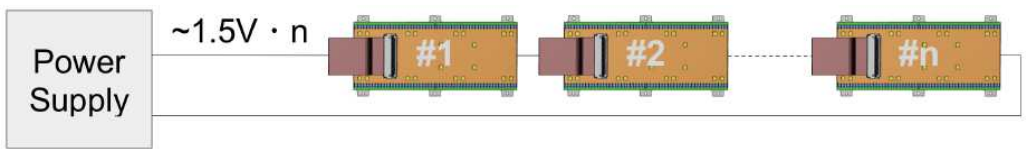
- Two main concepts:
  - Only two types of modules (1x2 and 2x2 chips) with a simple design



- Sensor
- ROC
- High Density Interconnect

  No extra ASICs

  - Serial powering to reduce power loss in the cable with an acceptable cable mass



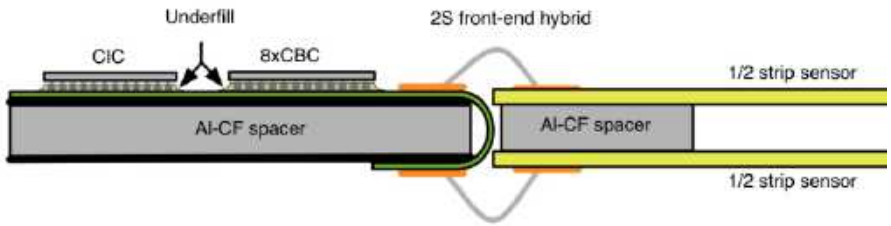
n~8-12

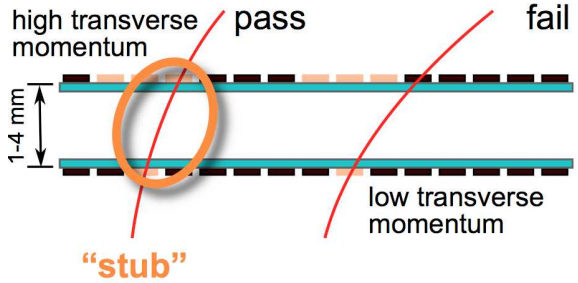
Extra complexity in the design:

- Low Drop Out regulator integrated in the ROC to convert the input current into a constant input voltage (1.2V)
- 2 (4) chips in one module connected in parallel => shunt on-chip to absorb the extra current in case of a failure of a chip

  2 ShuntLDO per chip (analog + digital domain): ROC and module cooling circuit designed for an efficient cooling of the hotspots

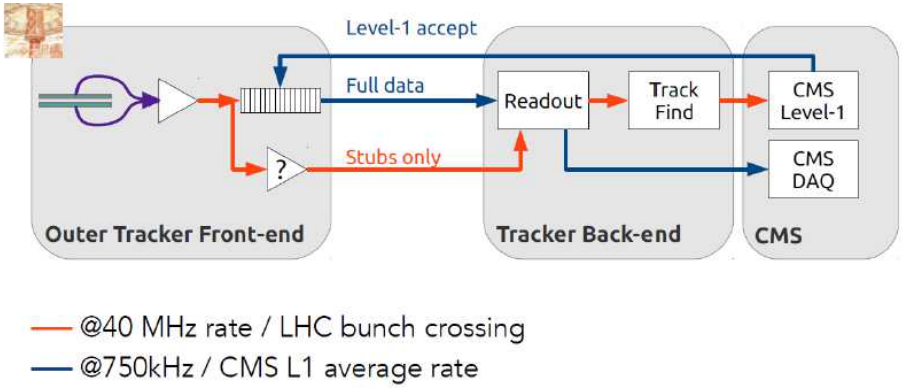
Outer Tracker: pT module concept





- Exploit the high B-field (3.8 T) of the CMS solenoid
- Modules made of two silicon sensors with a small spacing (from 1.6 mm up to 4 mm)
- Flex hybrid to route data from both sensors to one ASIC which performs cluster correlation between top/bottom sensor in a programmable search window

  Correlated clusters from high pT tracks => "stubs"
- Stubs are readout at each BX (40 MHz) and sent to L1 track finder

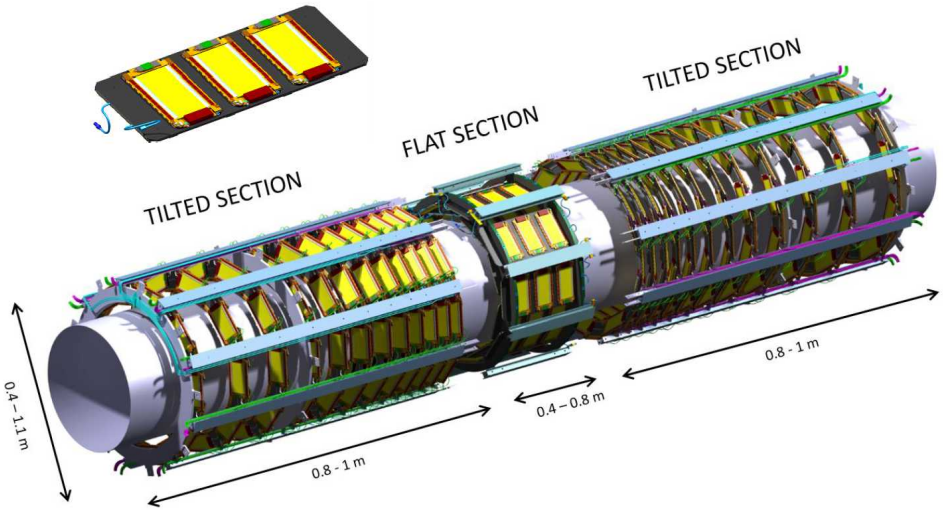


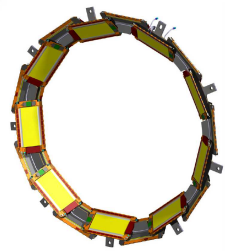
No other aggregator cards between the module and the back-end

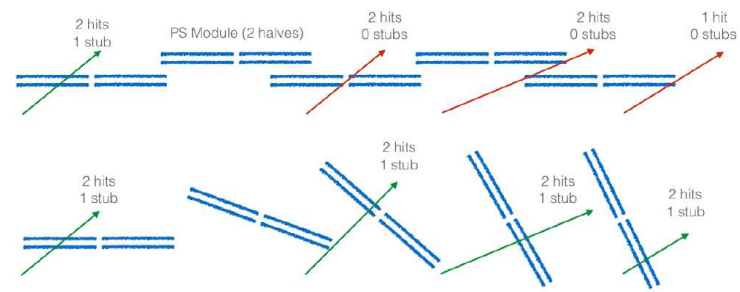
OT modules are self-contained units

OT intelligent layout

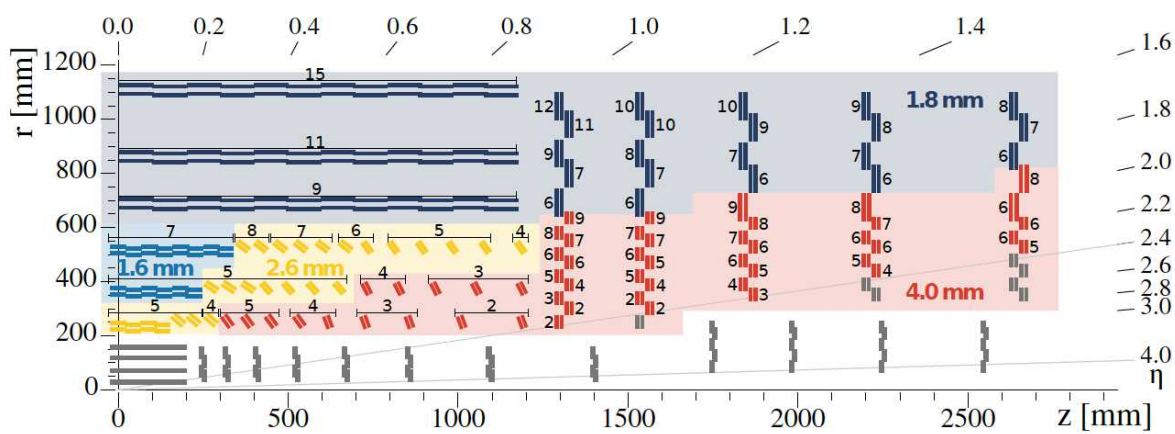
- Tilted barrel geometry fully efficient for inclined track stubs otherwise crossing top/bottom sensors in different modules







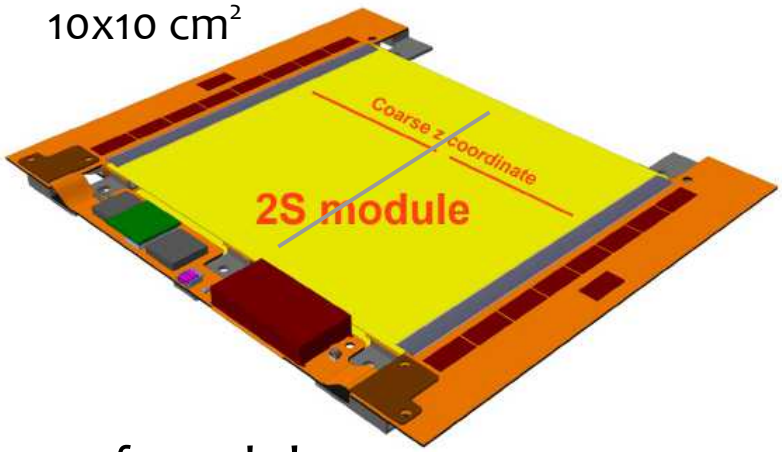
- Sensor spacing optimized in the different regions to guarantee efficient turn-on curves for stubs from pT=2 GeV tracks



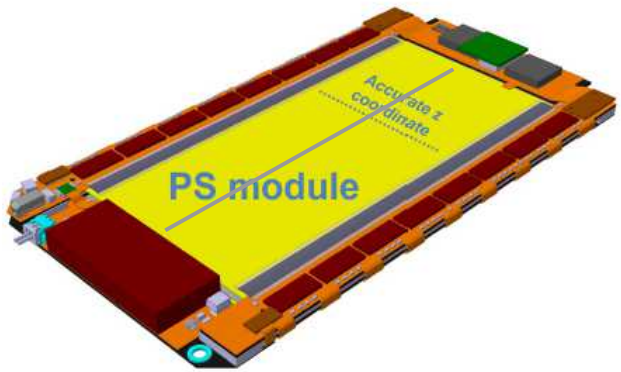
TDR layout

OT modules

10x10 cm^2

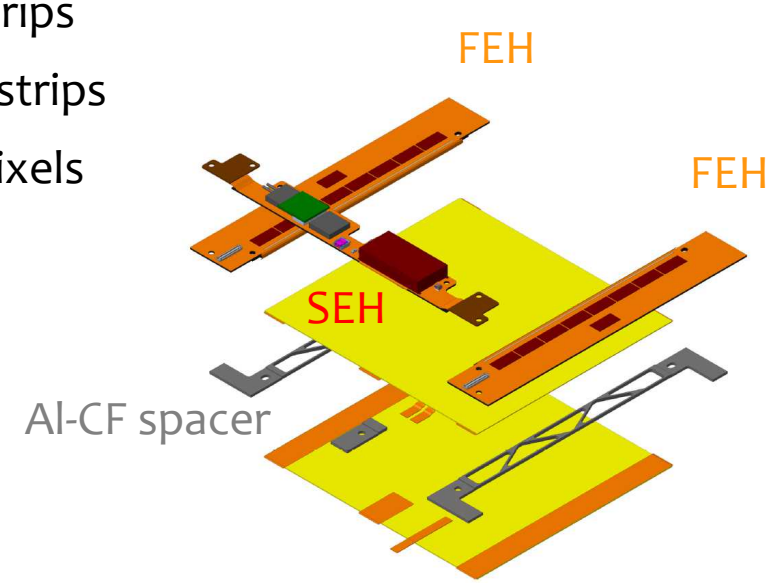


10x5 cm^2



- Two types of modules:
  - 2S: 2 sensors with 2 rows of 5cm x 90µm AC coupled strips
  - PS: 1 sensor with 2 rows of 2.4cm x 100µm AC coupled strips

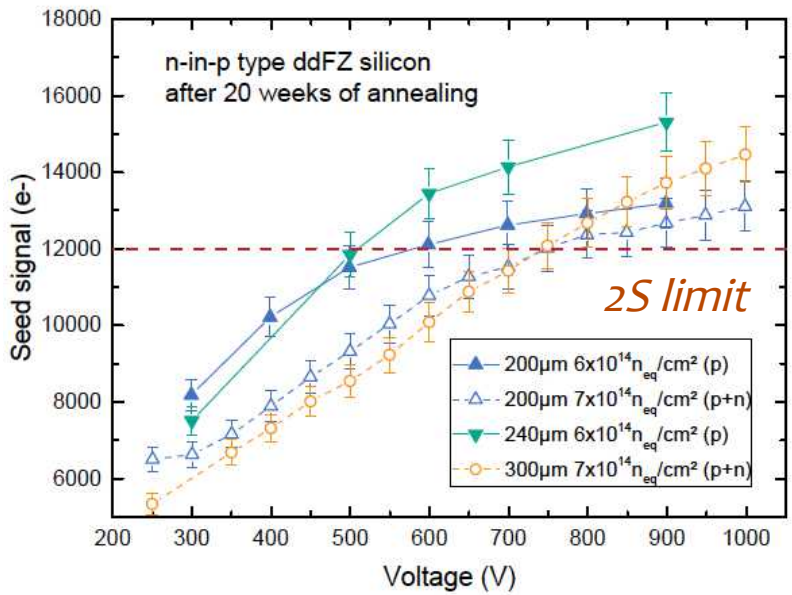
    1 sensor with 1.5mm x 100µm DC coupled macro-pixels
- Modules are self-contained units:
  - Front-End Hybrid: readout and concentrator ASICs
  - Service Hybrid: DC-DC converter + data-link
  - Sensors
  - Al-CF spacer



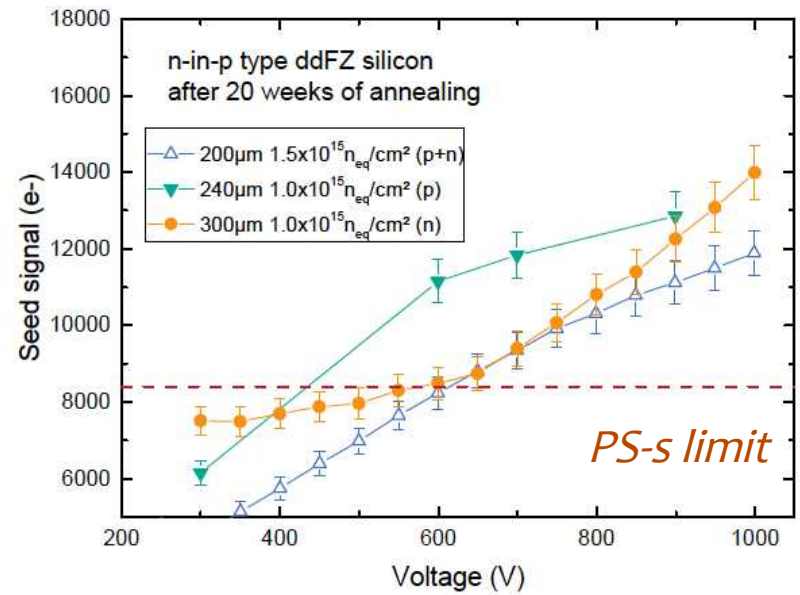
- Correct stub finding poses stringent requirements on the accuracy of the mechanical assembly (max rotation in 2S modules: $\Delta\phi$<400 µrad)

OT sensors

2x typical expected fluence for 2S



1.5x typical expected fluence for PS

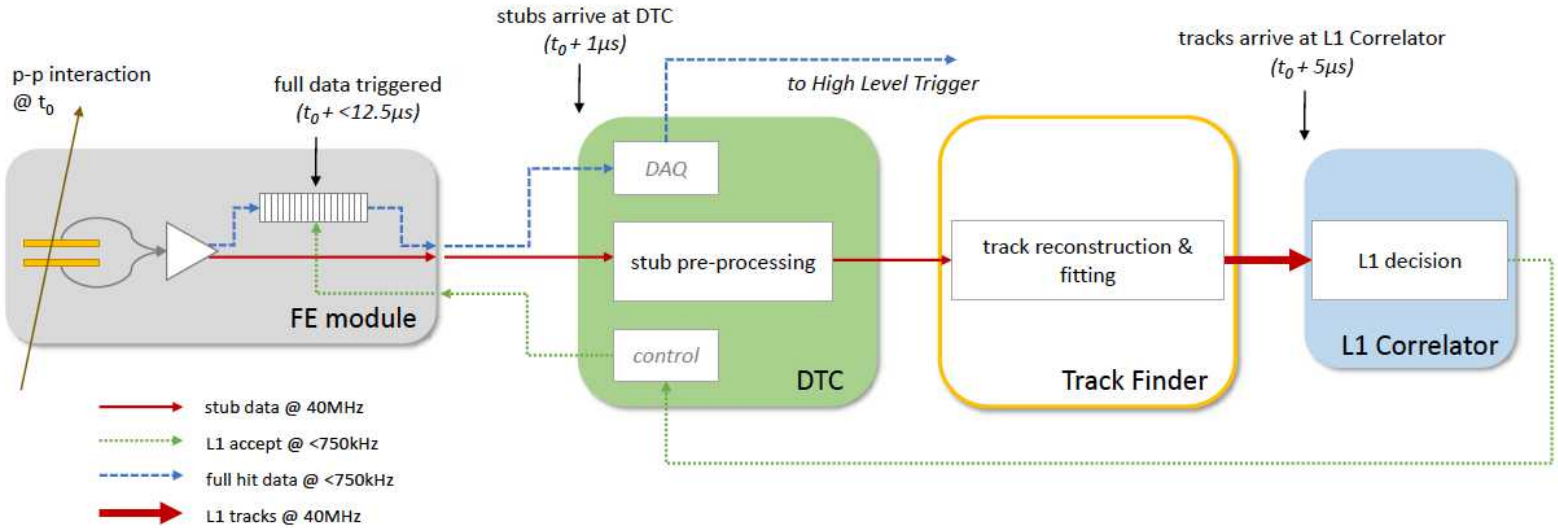


- OT has a binary readout electronics

  The figure-of-merit is the charge collected on a single seed-channel

  - **Strip**: ENC is 1000e for CBC chip (2S module), 700e for SSA chip (PS-s module)
    - Thin sensors (200-240 µm) operated at nominal bias (600V) provide enough charge after irradiation even at 1.5x the expected fluence (10% more charge in 240 µm sensors)
    - Charge on seed-strip is stable vs. annealing time for thin sensors
  - **Macro-pixel**: ENC is 200e for MPA (PS-p module) => less stringent requirements Thin sensors (200 µm) sufficient

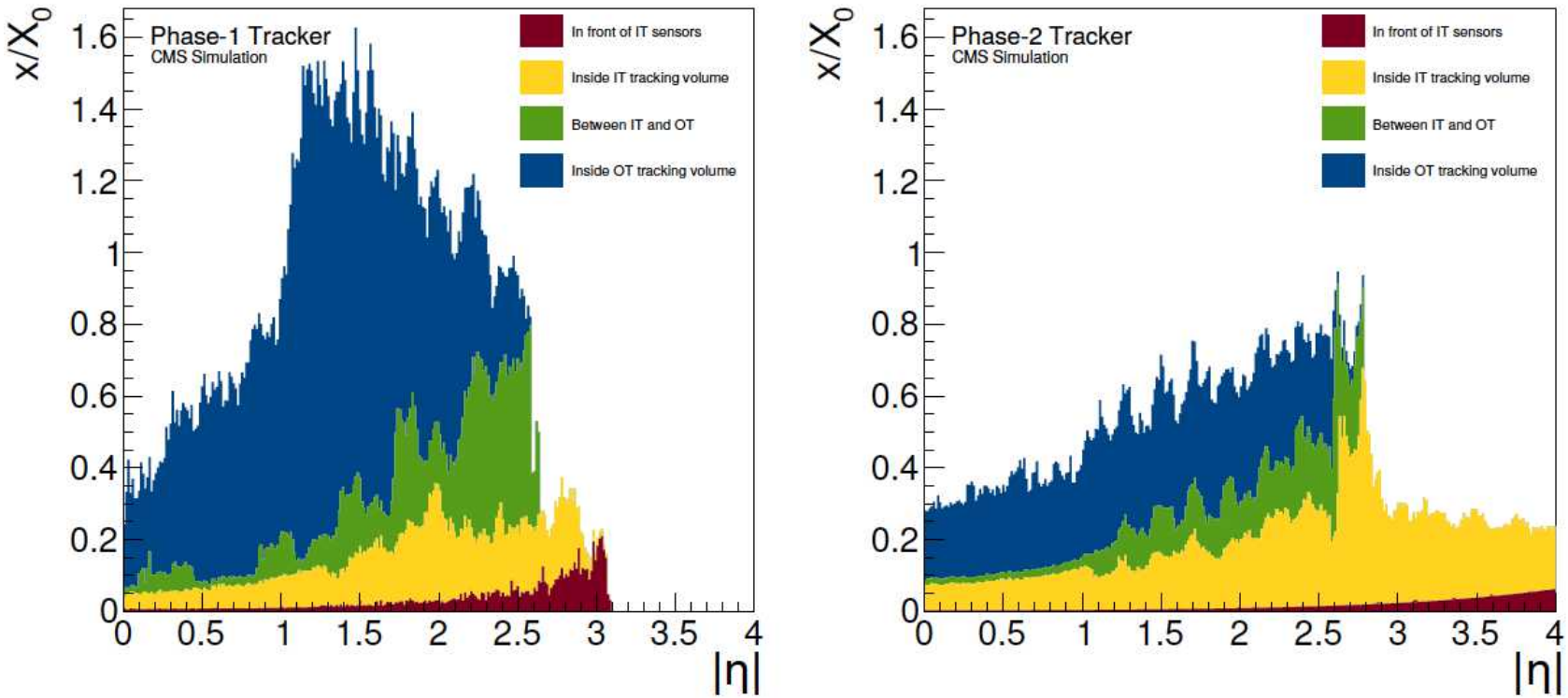
OT back-end electronics



- Data from 72 OT modules are sent to 1 DTC board which unpacks the stubs and converts the information from local to global coordinates
- Track Finder Processor receives data sliced in space and time (time-multiplexing: 1 event for 1 TFP node) and performs pattern recognition and track finding using commercially available FPGAs
- Two different approaches for pattern recognition and track fitting developed and verified in real life on two TFP hardware demonstrators
  => latency below the **4 μs** spec (time budget for L1 track finding) for both

More details in Tom James's talk on Thursday

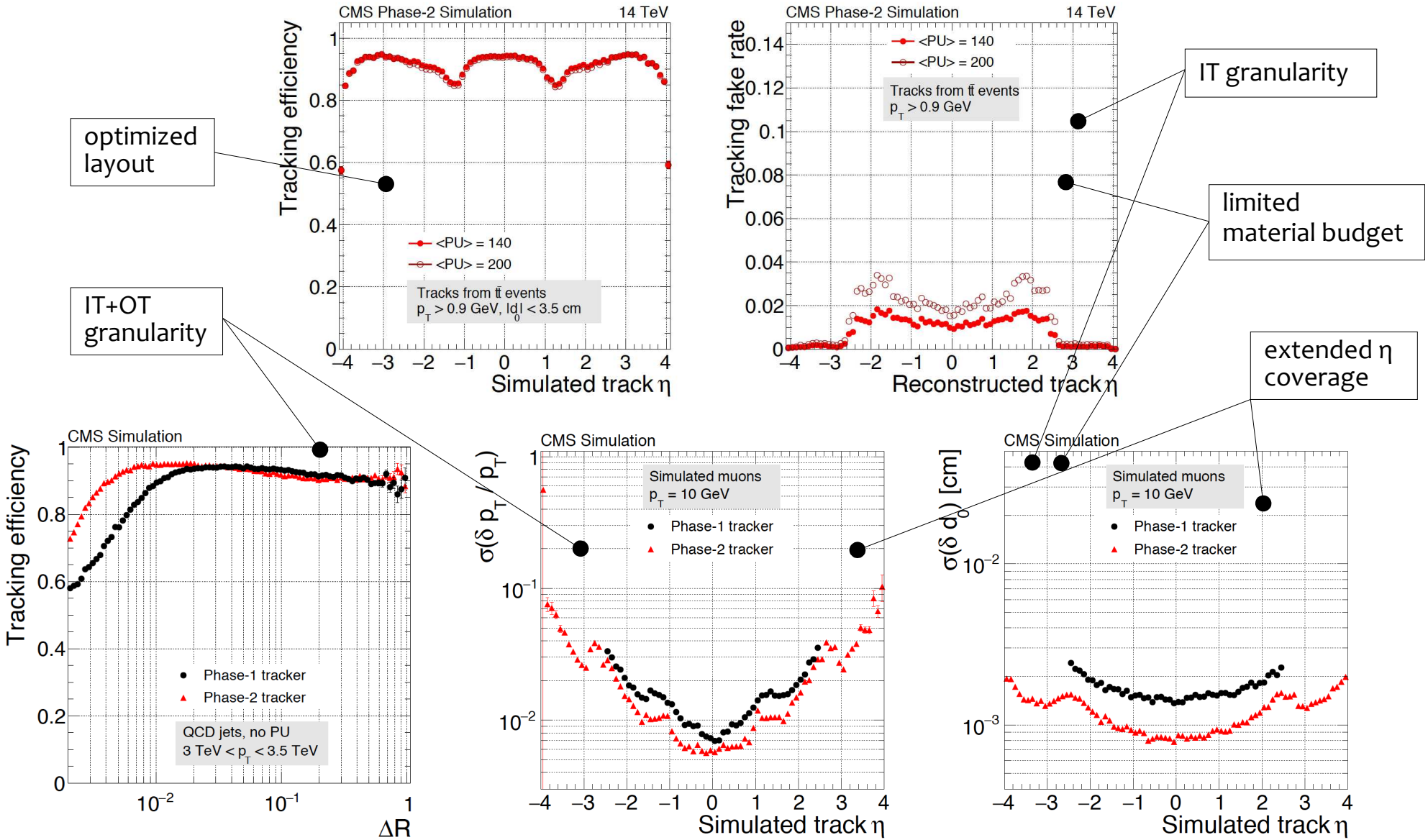
Material budget



- Huge effort to limit the amount of passive material despite the huge power required (IT: 50 kW, OT: 100 kW)
  - optimized layout (reduced number of layers/discs and better orientation of the modules)
  - optimized powering scheme (serial powering in IT, DC-DC converters in OT)
  - optimized routing of the services from the early stages of the design of the detector
  - choice of evaporative CO_2 cooling (small diameter/low mass pipes)

Design tracking performance

- Guarantee fully efficient tracking in high pileup conditions with resolution on offline track parameters as good or better than the current tracker and on extended η range



Summary

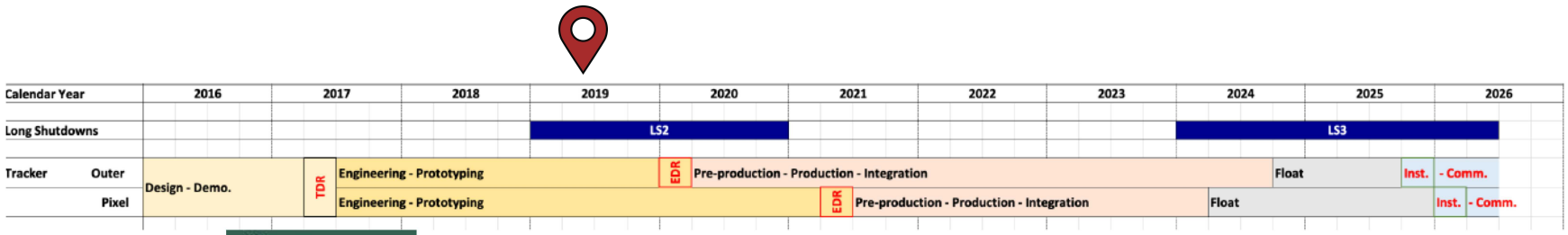
- The upgraded CMS Tracker for HL-LHC will be a key ingredient for the CMS physics program after 2026
- In all the critical areas the project is moving from the R&D phase to the construction of demonstrators fully functional in the extreme conditions of HL-LHC
- Numbers of the project are huge (3892 IT modules + 13296 modules in OT)

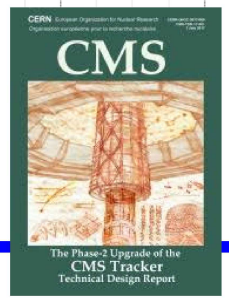
  Challenges ahead of us

  - large scale/high quality production of the components
  - extreme care in system and integration aspects

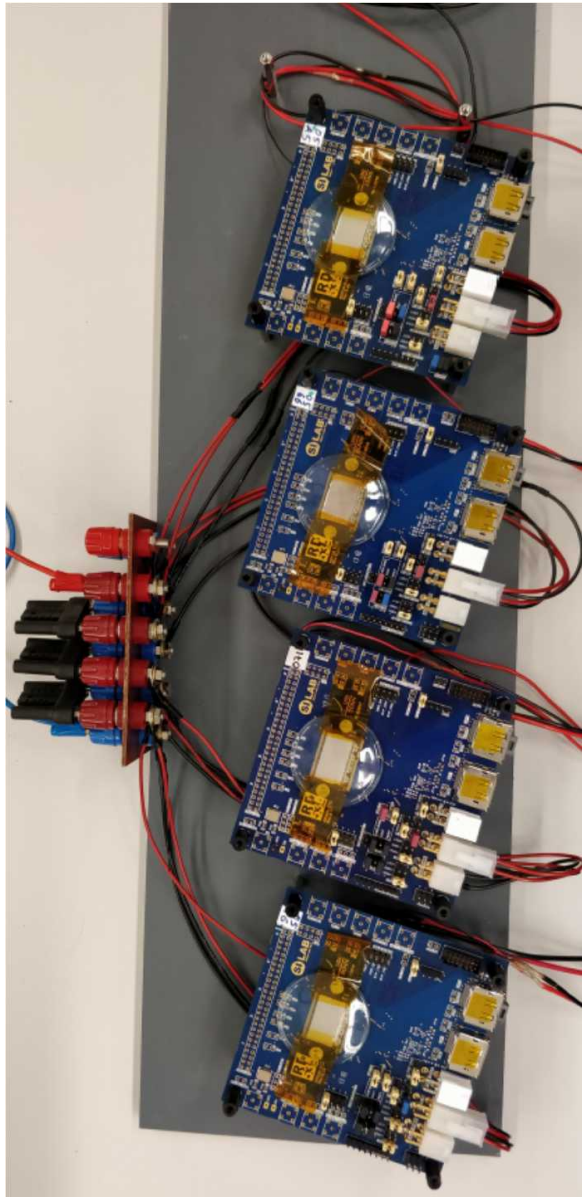
EXTRA SLIDES

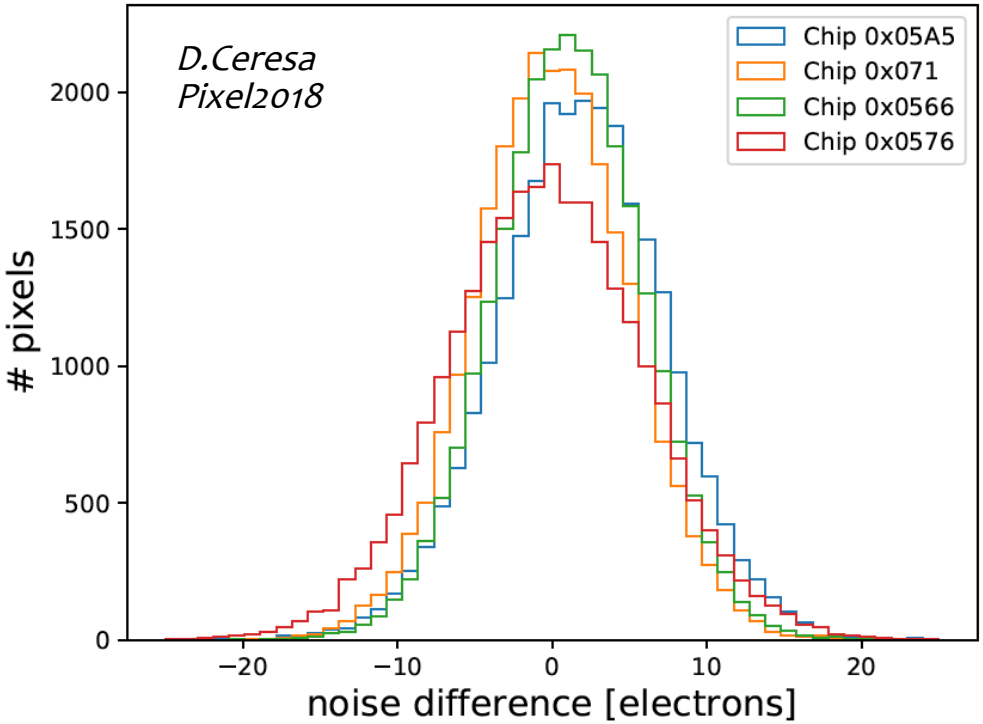
HL-LHC and CMS Tracker upgrade timeline





IT modules and powering scheme





- Pixel-by-pixel difference of the noise between parallel powering and serial powering (4 RD53A chips)
  => no deterioration when operating in chain
- Distribution of the HV ground for modules in the same chain under investigation