The CMS Tracker Upgrade for the High Luminosity LHC

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on behalf of the CMS Collaboration

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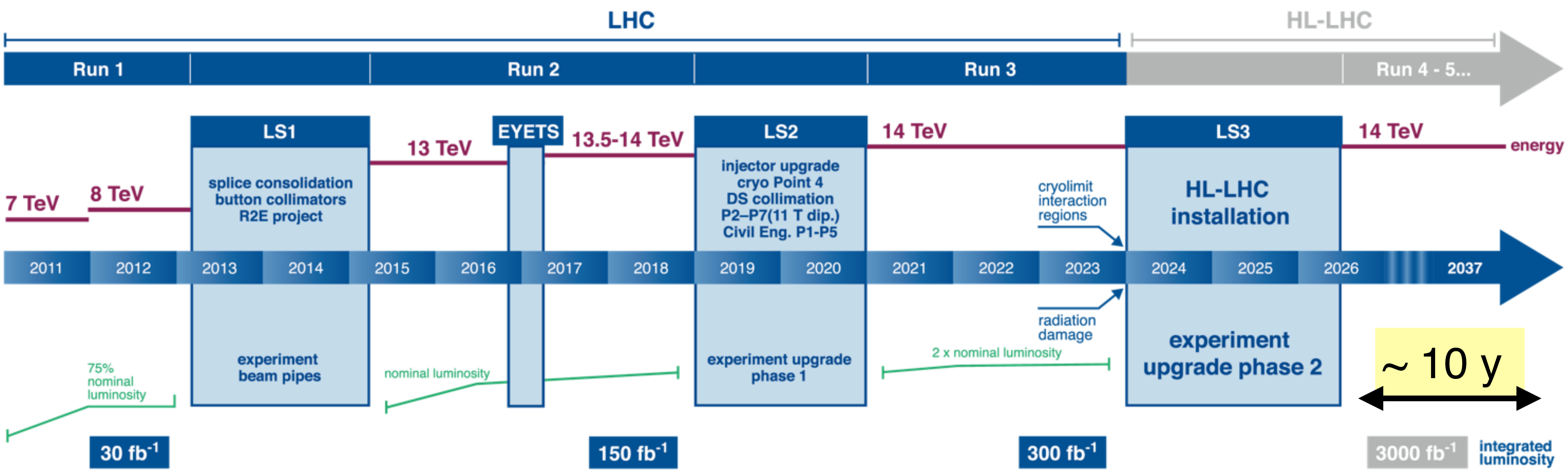
EUROPEAN PHYSICAL SOCIETY HEP2019

The HL-LHC technological challenge



int. lumi 3000-4500 fb^{-1}

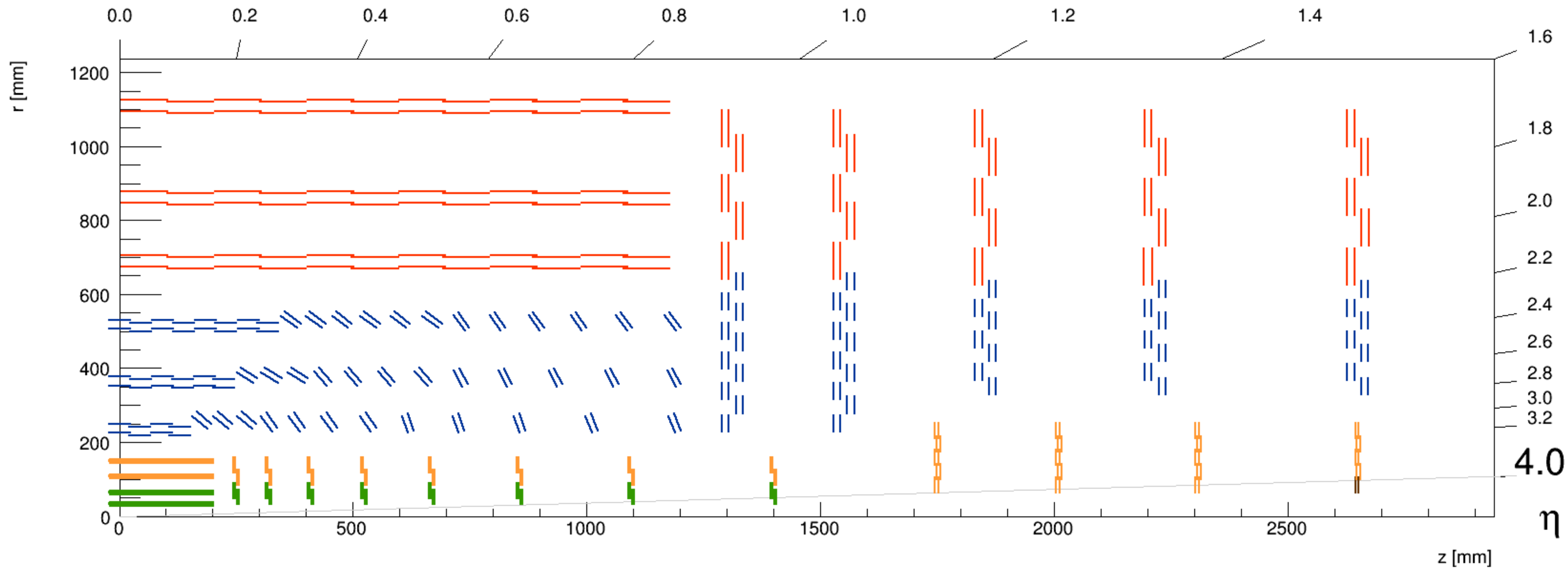
inst. lumi: 5-7.5 x 10^{34} $cm^{-2}s^{-1}$

→ <PU> ~ 140-200

- dose & fluence: 10 x higher
- 750 kHz L1 rate
- 12.5 μs L1 latency

The present CMS tracker cannot sustain the implied radiation levels and data rates and has to be completely replaced

The CMS Tracker for HL-LHC

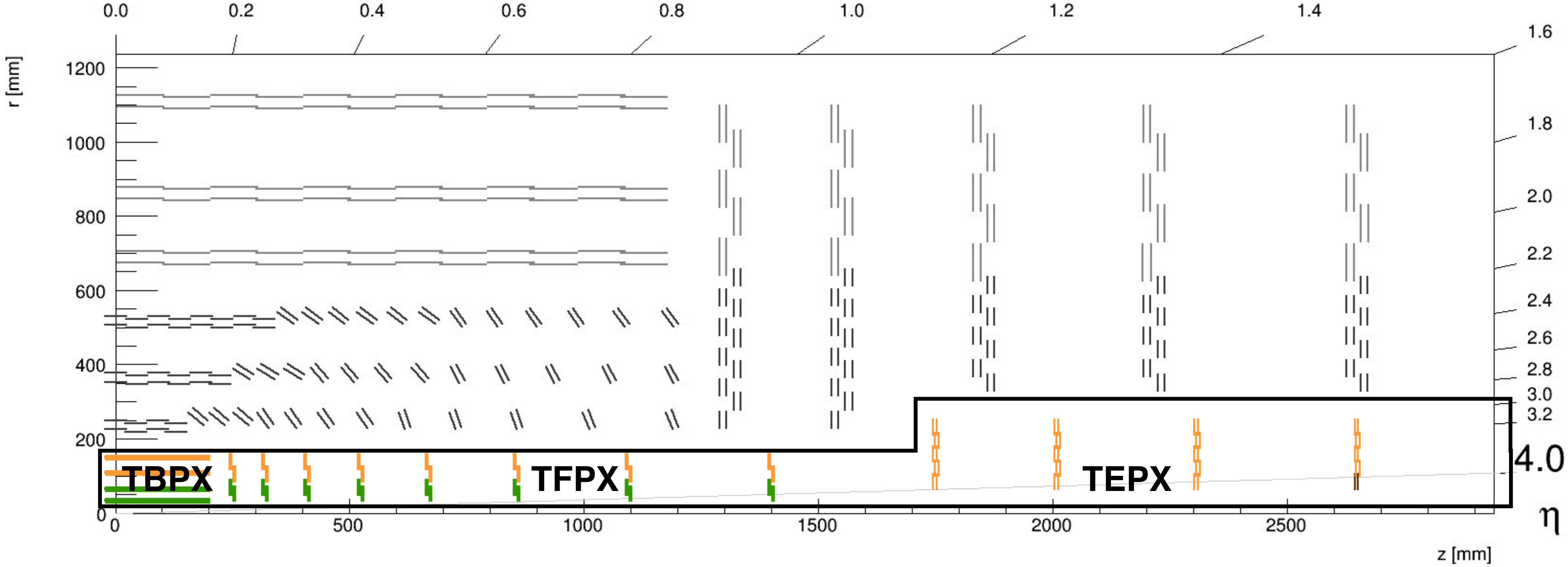


Key features:

- contribute to L1 trigger
- extended tracking coverage (up to η=4)
- high granularity and high bandwidth
  - up to 3.5GHz/cm^2 occupancy (first layer @ 3cm from beam line)

- Thin n-in-p silicon sensors
- Operation at -20 ^{0}C
- reduced material budget for improved tracking performance in high PU scenario

The Inner Tracker

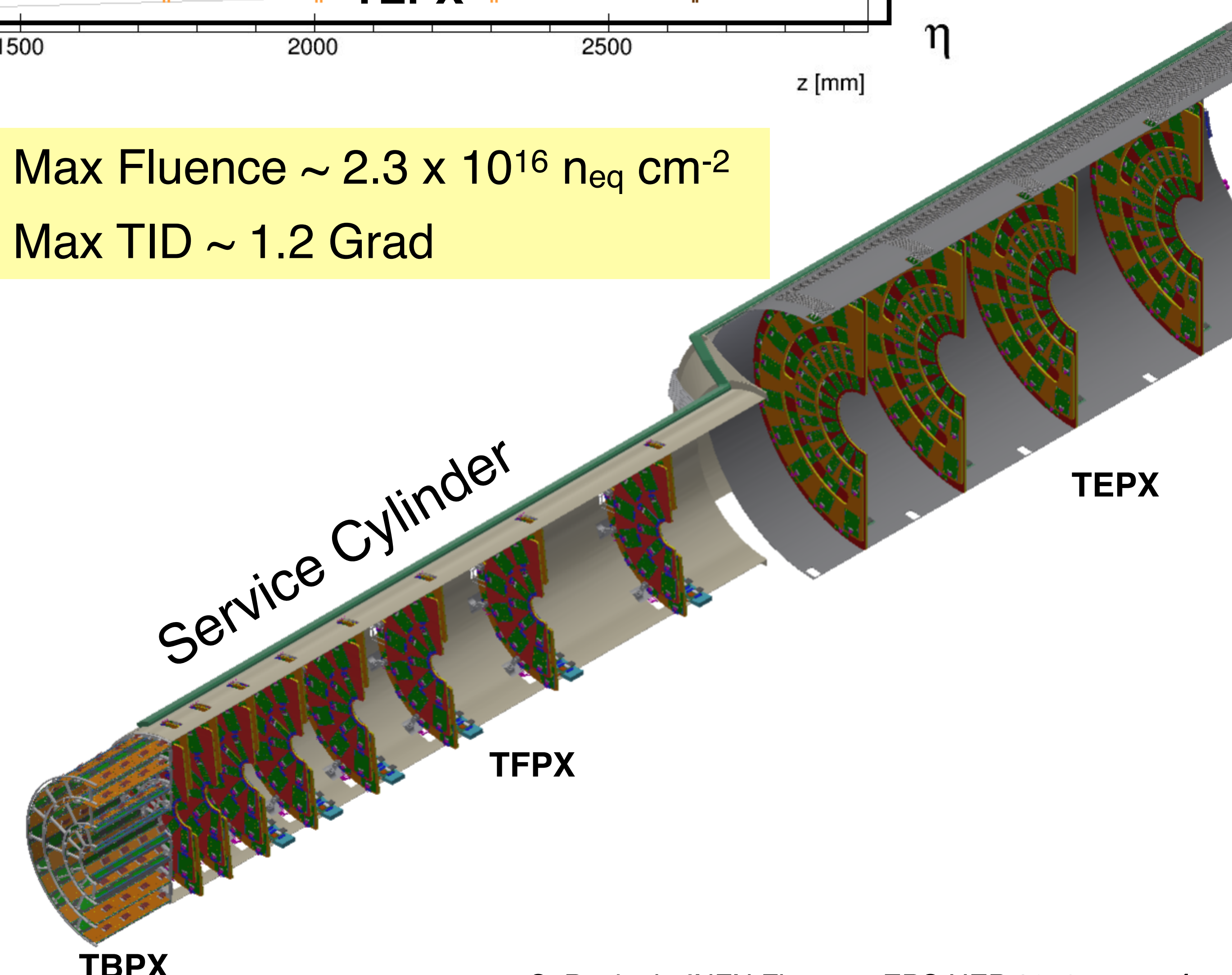


Max Fluence ~ 2.3 x 10^{16} n_{eq} cm^{-2}

Max TID ~ 1.2 Grad

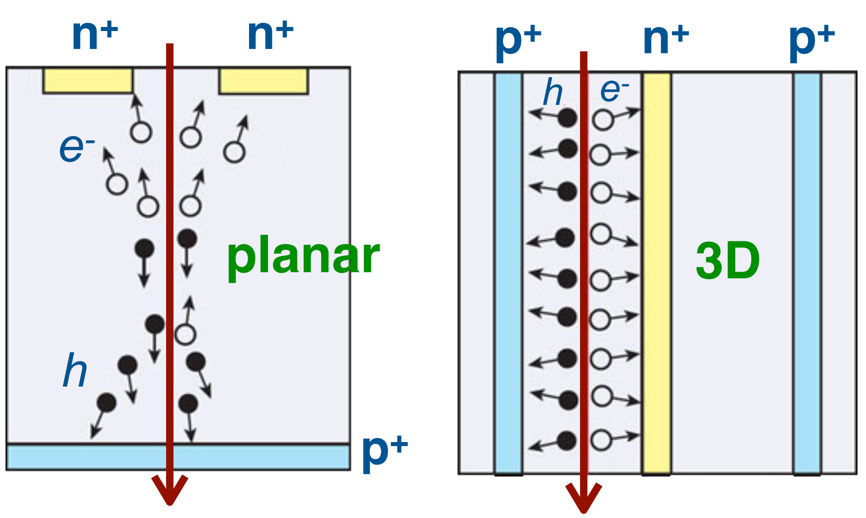
Inner Tracker:

- 3900 modules, 4.9 m^2, 2×10^9 pixels
- occupancy: < 0.1%
- Hybrid modules with 2 (1x2) or 4 (2x2) readout chips
- Coverage up to |η| = 4.0
- Simple mechanics:
  - can be removed for maintenance during LHC shutdowns
  - Barrel: splits in half at z~0
  - Disks: planar geometry (no turbines)



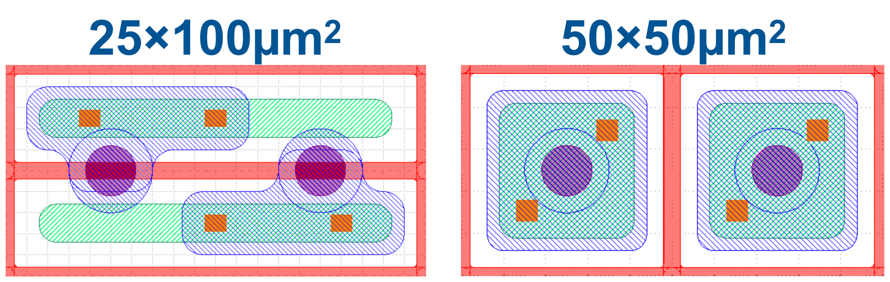
IT: Radiation hard pixel silicon sensors

Planar thin (100-150 μm thick) **n-in-p** pixel sensors:
- up to 0.8-1kV bias @ end of lifetime
- spark protection between r/o chip and sensor



3D sensors option for innermost layers:
+ more radiation hard
+ lower bias needed
- larger cell capacitance
- more complex fabrication

Small pitch pixel cells.
Two aspect ratios under study (same bump bonding pattern):



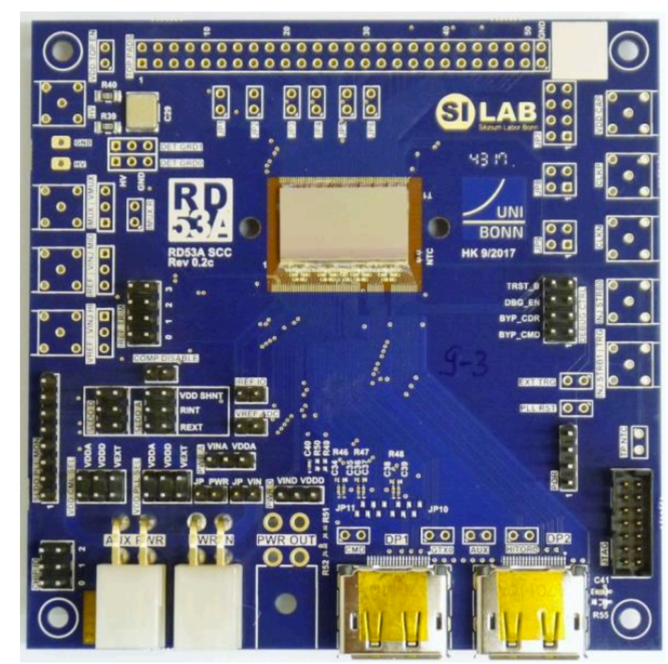
keep occupancy < 0.1%

Extensive R&D still ongoing:
More in Davide Zuolo's presentation later in this session

IT: radiation hard readout chip

- Being developed by the RD53 Collaboration
  - both ATLAS and CMS inner detectors
- 65 nm CMOS technology
- 50x50 μm^2 cell size
- low-threshold ($\lesssim$ 1000 e^-)
- high hit and trigger rate:
  - 160 Mbps control & up to 4 x 1.28Gbps output links
- Support for serial powering scheme
- chip size(CMS): 16.8 x 21.6 mm^2 (336 x 432cells).

- RD53A: first prototype (~1/2 size of final chip)
- technology and design concepts demonstrated, lot of R&D performed:
  - Radiation hardness tested above 500 Mrad

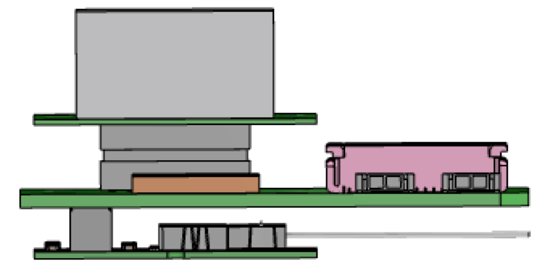


CMS r/o chip prototype submission in 2020

IT: Link to DAQ and CTRL

Backend electronics (DTC)

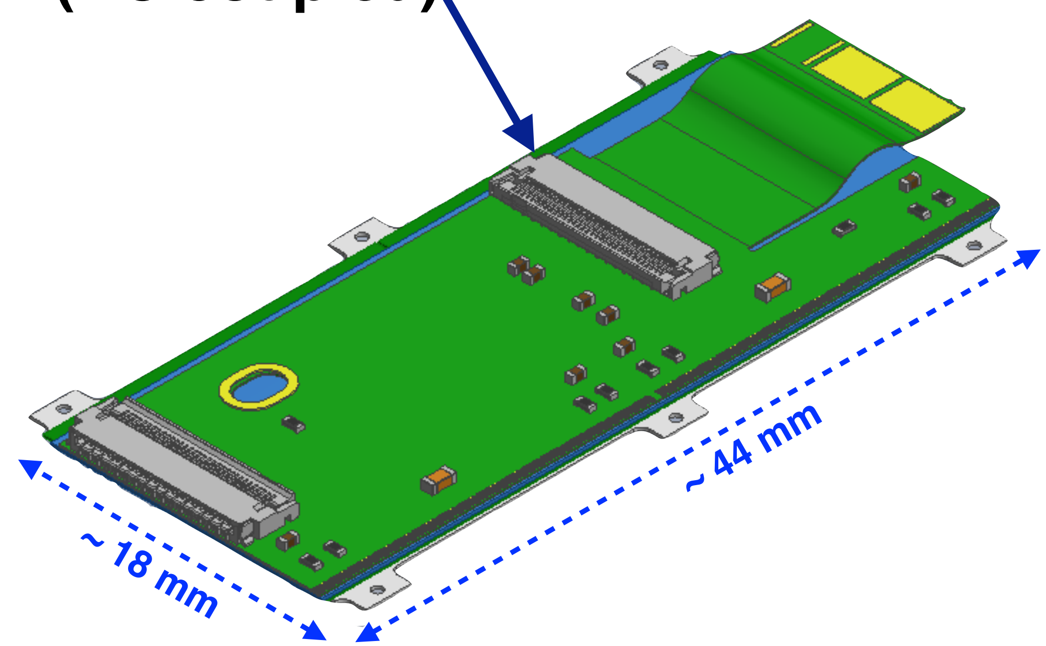
DAQ and CTRL



"Portcard": opto-link

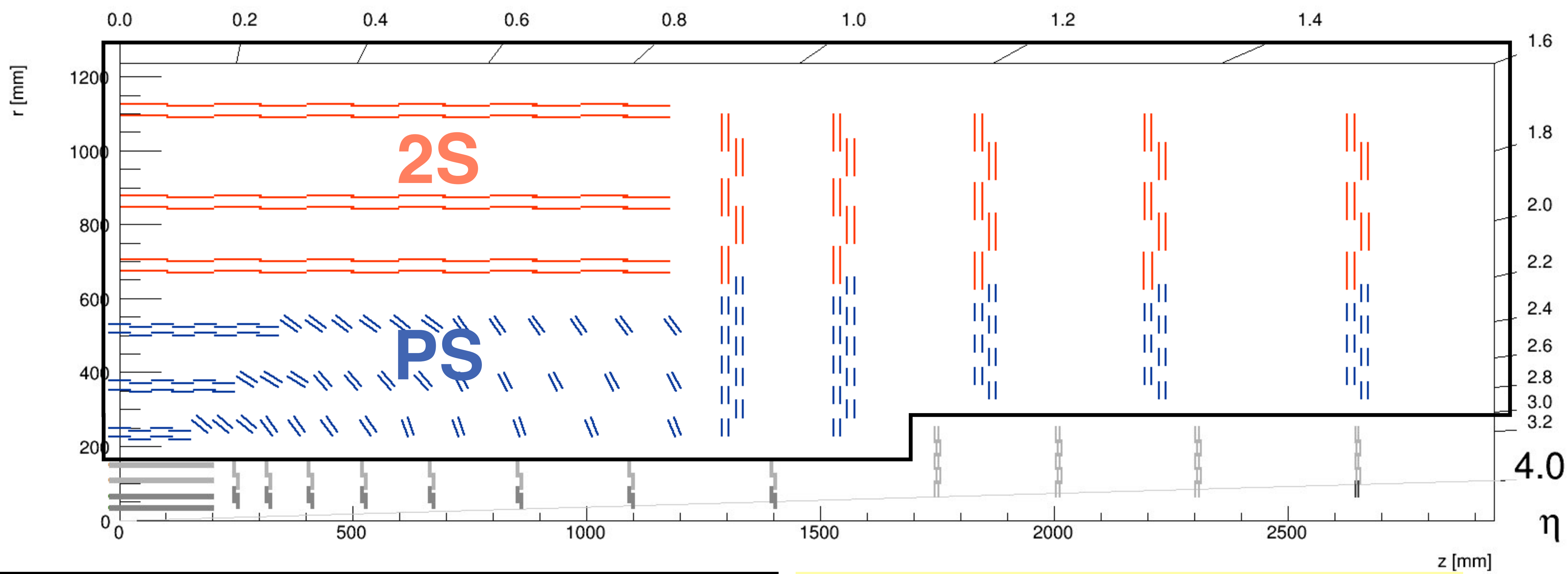
tw Pairs (max 1.2 m), Flat flex (max 0.5 m)

1.28 Gbps (AC coupled)



- ~ 750 opto-boards ("portcards") integrated in the Service Cylinder implement advanced optical links communicating with the DAQ and Control backend systems
- **AC-coupled e-links** ensure the communication between the r/o chip and the portcards:
  - Up to 6 up-links @1.28 Gb/s per module
  - One down-link @160 Mb/s per module
- A **High Density Interconnect** flex-circuit provides decoupling capacitors and connectors to data e-links and power
- The r/o chip is the only active component in IT modules

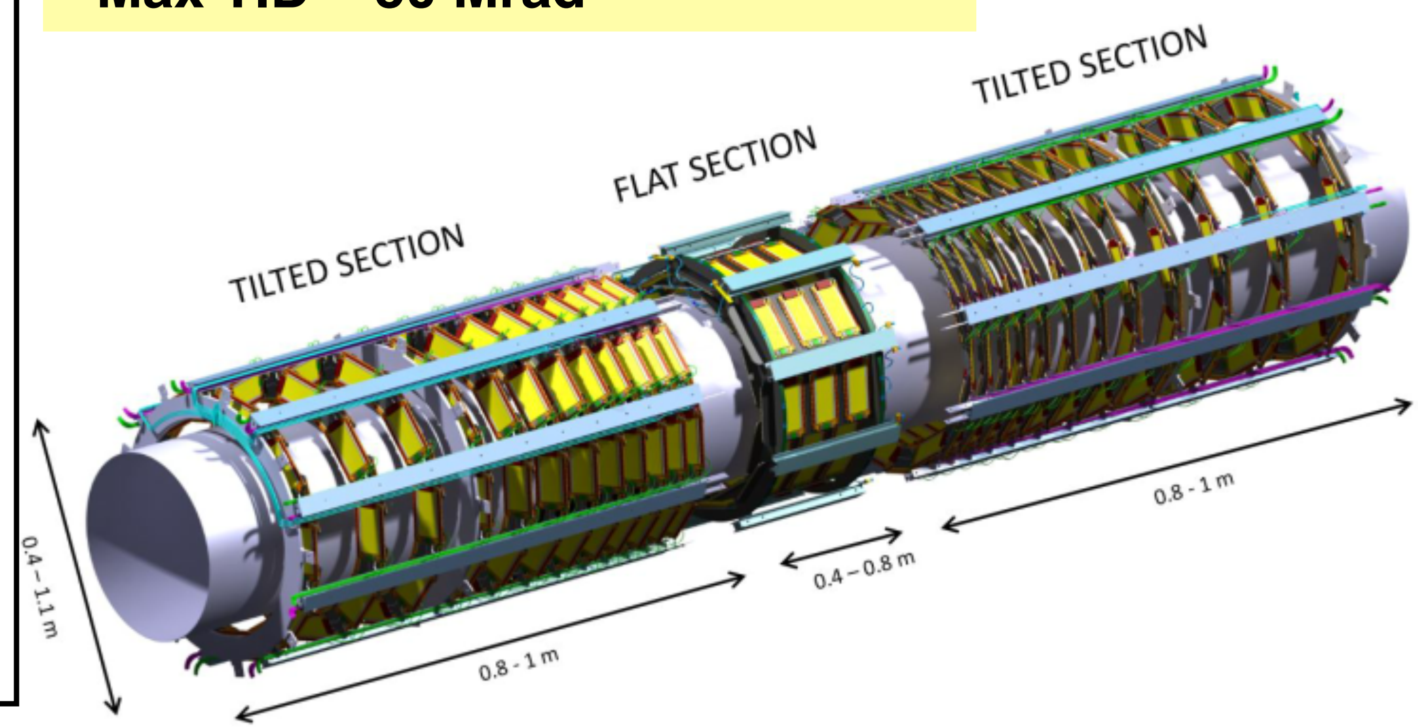
The Outer Tracker



- **13200 "Pt modules"** (providing L1 primitives):
  - Strip-Strip (2S)
  - macroPixel-Strip (PS)
- L1 Coverage up to |η| ~ 2.5
- 192 m², 42M strips, 170M macro-pixels
- occupancy < 1%
- Innovative tilted geometry in the inner barrel
  - reduces #PS modules → (mass and cost)
  - better trigger performance

Max Fluence ~ 1 x 10^{15} n_{eq} cm^{-2}

Max TID ~ 50 Mrad



Tracking @ L1 trigger

P_t resolution, e-γ discrimination, isolation → better trig selectivity needed to exploit high luminosity:

- An FPGA-based "track-finder" system performs pattern recognition + track fitting
- The track finder processes "stubs" relative to tracks with $P_t > 2$GeV sent by the Outer Tracker

More about the HL-LHC CMS L1 trigger in the talk by Cecile Sarah Caillol tomorrow morning

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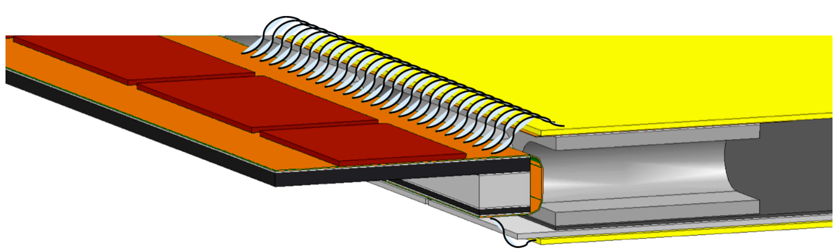
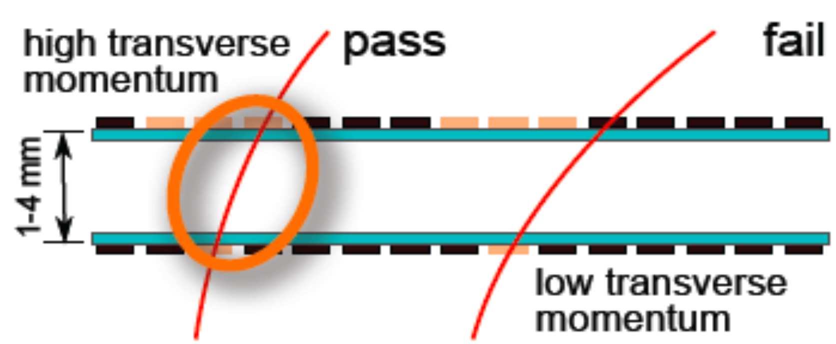
P_t discriminating module concept:

- two silicon sensors with small spacing in a module
- one ASIC correlates data from both sensors selecting tracker “stubs”





distance depends on layer radius:
→ keep selectivity p_t >2GeV/c

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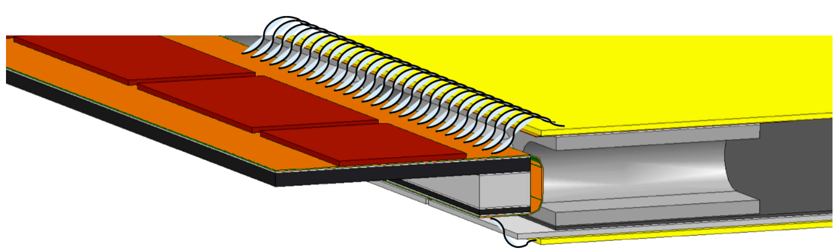

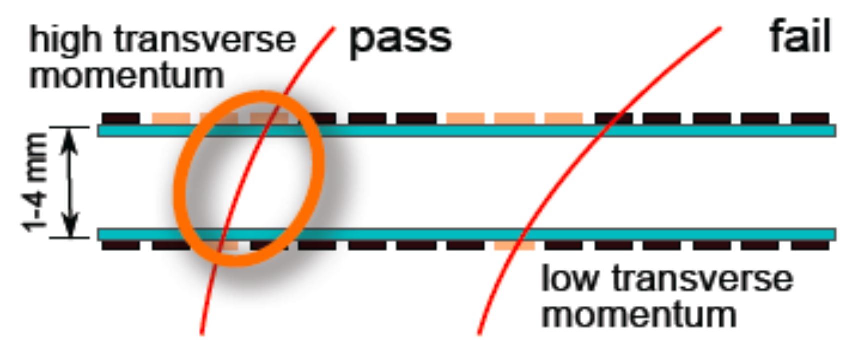

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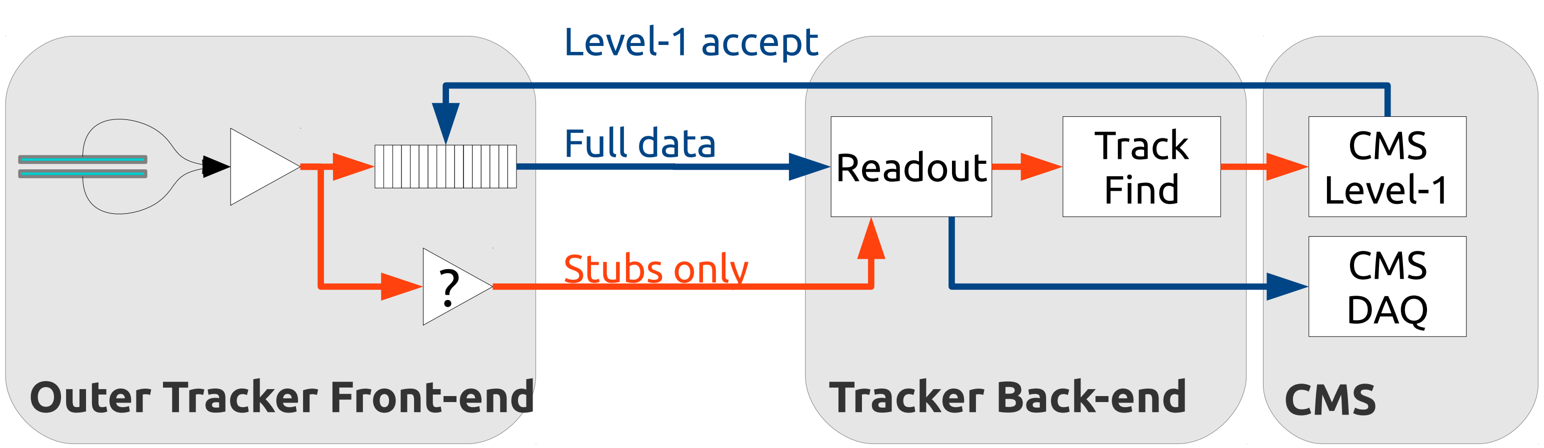
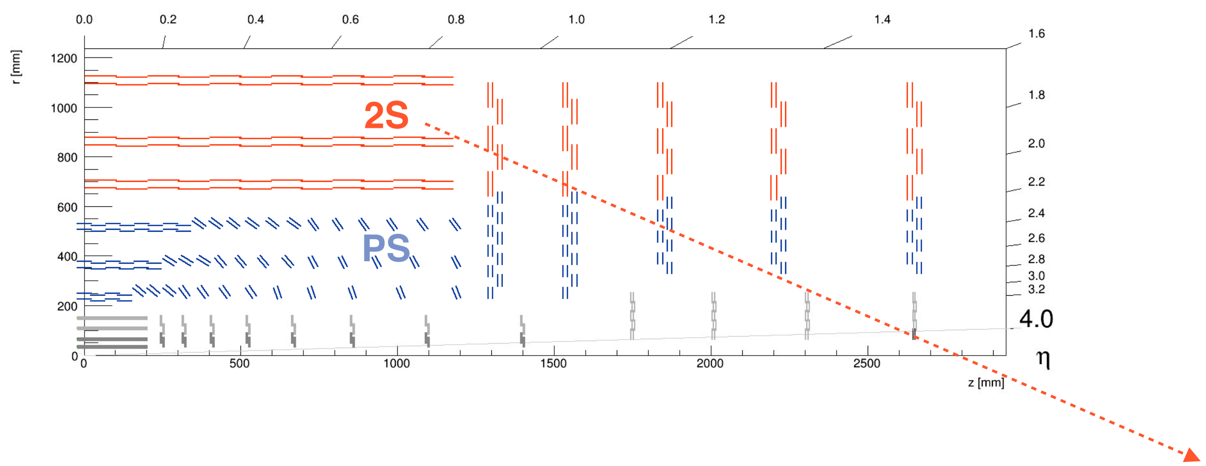


"stubs" are sent to the track finder backend, and used to create L1 track primitives with p_t>2GeV/c @ 40MHz

@ 40 MHz – Bunch crossing
@ 750 kHz – CMS Level-1 trigger

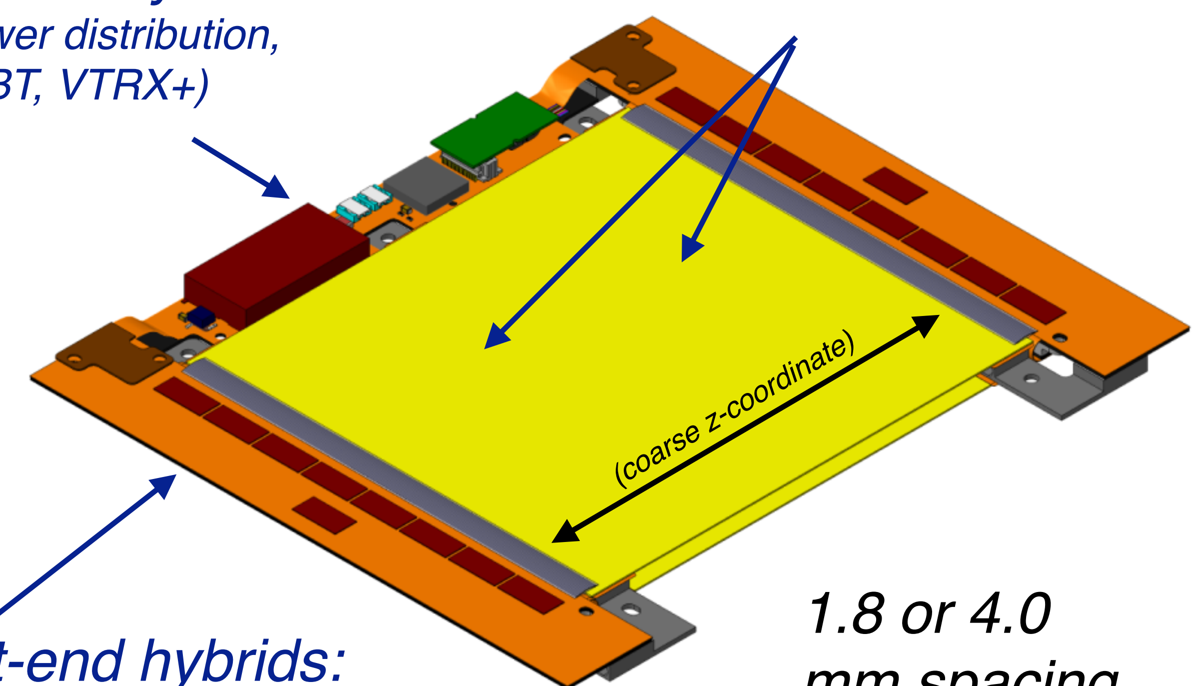
Two basic types of OT Modules



Strip-Strip (2S) modules:

90 cm² active area
2 × 1016 strips 5cm × 90 µm

service hybrid
(Power distribution, lpGBT, VTRX+)



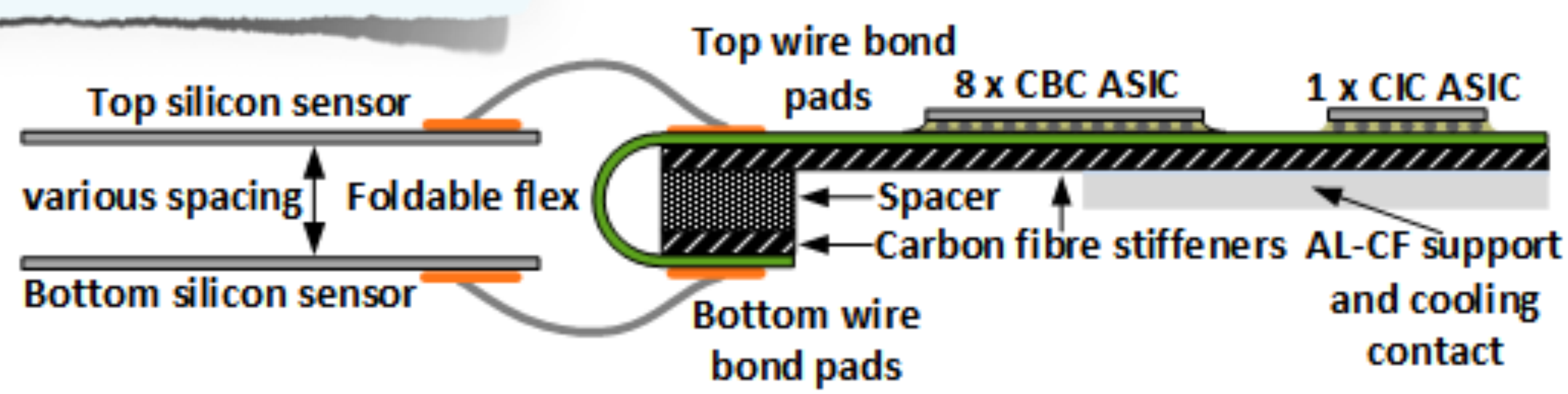
front-end hybrids:
8 CBC readout ASICs
1 Concentrator (CIC) ASIC

1.8 or 4.0 mm spacing

lpGBT = low-power Gigabit Transceiver
VTRx+ = Versatile Link Plus Transceiver

CBC = CMS Binary Chip
→ readout and L1 stub finding

CIC = Concentrator Integrated Circuit
Receives L1 information and readout data
"Data hub" to service hybrid



Two basic types of OT Modules

Each module is a functional unit individually connected to:

- backend power system
- DTC (= Data, Trigger and Control) system via advanced optical links
- no token control rings
- no intermediate power grouping

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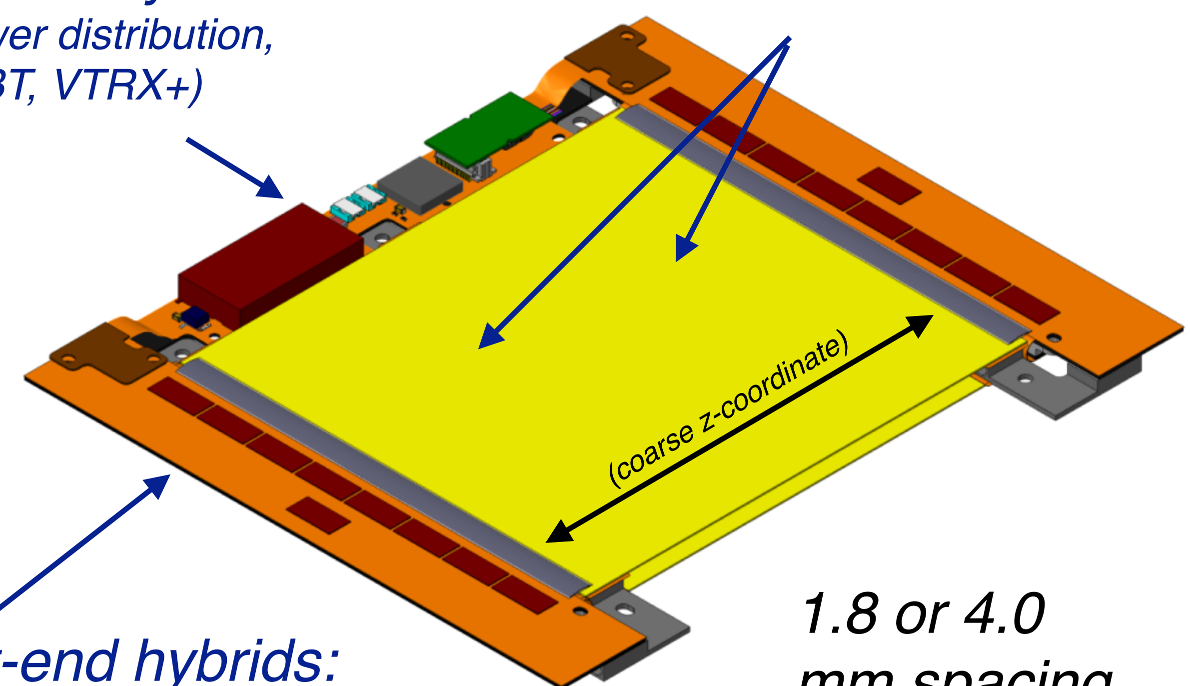

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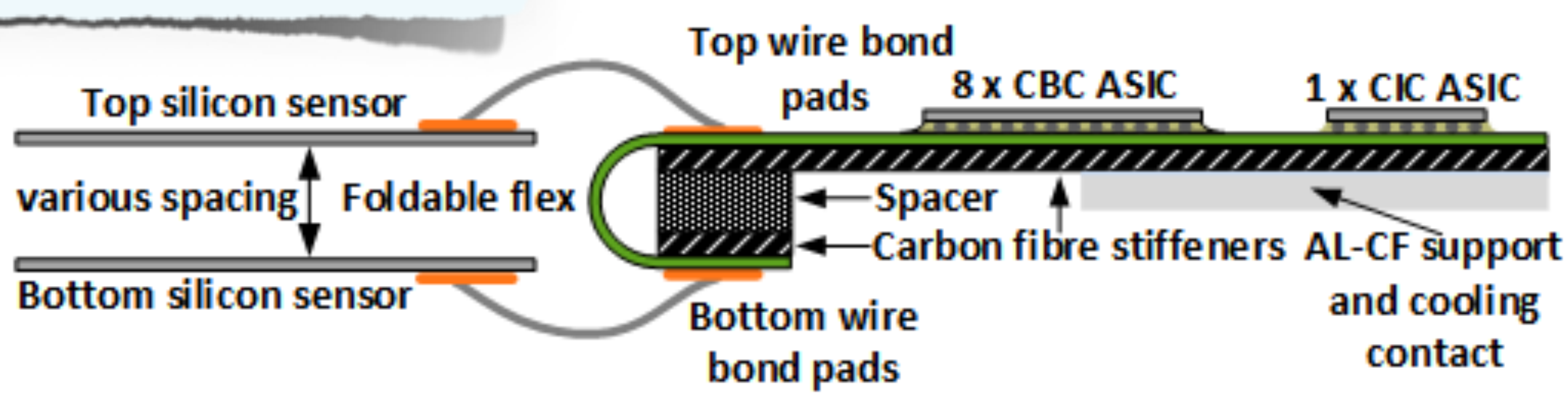

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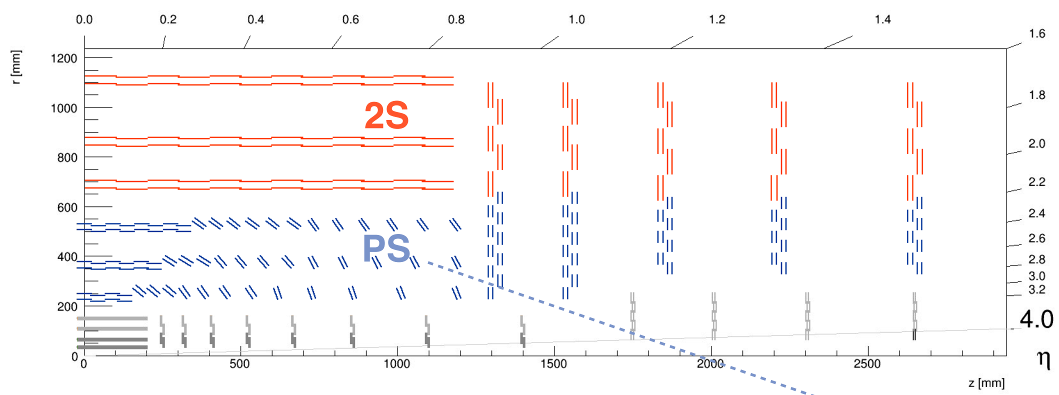


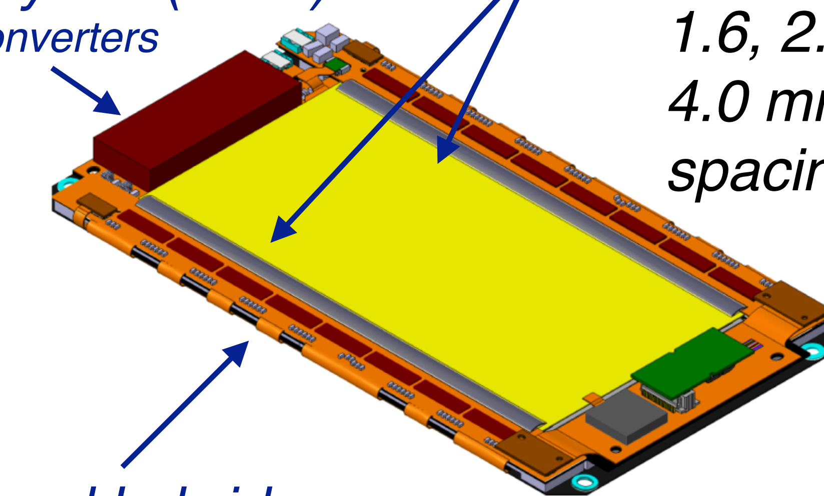
Macro Pixel-Strip (PS) modules:

45 cm² active area:

- *2 × 960 Strips 2.5 cm × 100 µm*
- *32 ×960 macro-pixels 1.5 mm × 100 µm*

power hybrid (POH)
DC/DC converters

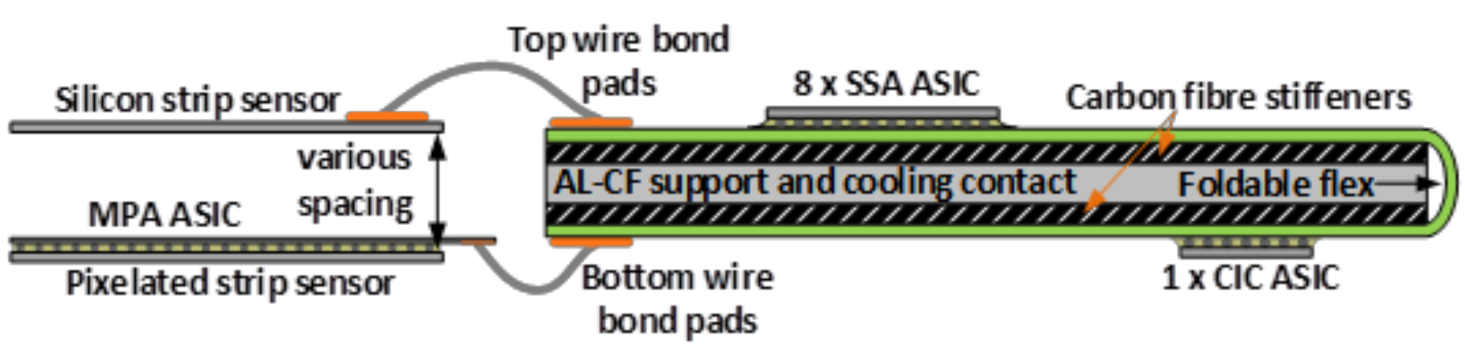
1.6, 2.6 or 4.0 mm spacing



front-end hybrids:
8 SSA readout ASICs
1 Concentrator (CIC) ASIC

readout hybrid (ROH)
lpGBT + opto module

SSA = Short Strip ASIC → readout of short strip sensors
MPA = Macro Pixel ASIC → readout of Macro Pixel sensors



- Large area + high granularity → large number of channels
- thin sensors → low signal → low threshold and low noise analogue circuits
- high data bandwidth + long (12.5 μs) L1 latency → high digital activity

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↓

IT ~ 50 kW

OT ~100 kW

→

High Power Budget

more then 3 times the phase1 tracker

- ~ same available total cable cross section
- keeping low material budget
- delivered at ~ 1÷1.2 V

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Different power distribution strategies:

- **OT**: 6-11 V **parallel powering** with **on-module conversion** (rad-hard DC/DC converters)
- **IT**: **serial powering** (up to 12 modules per chain)

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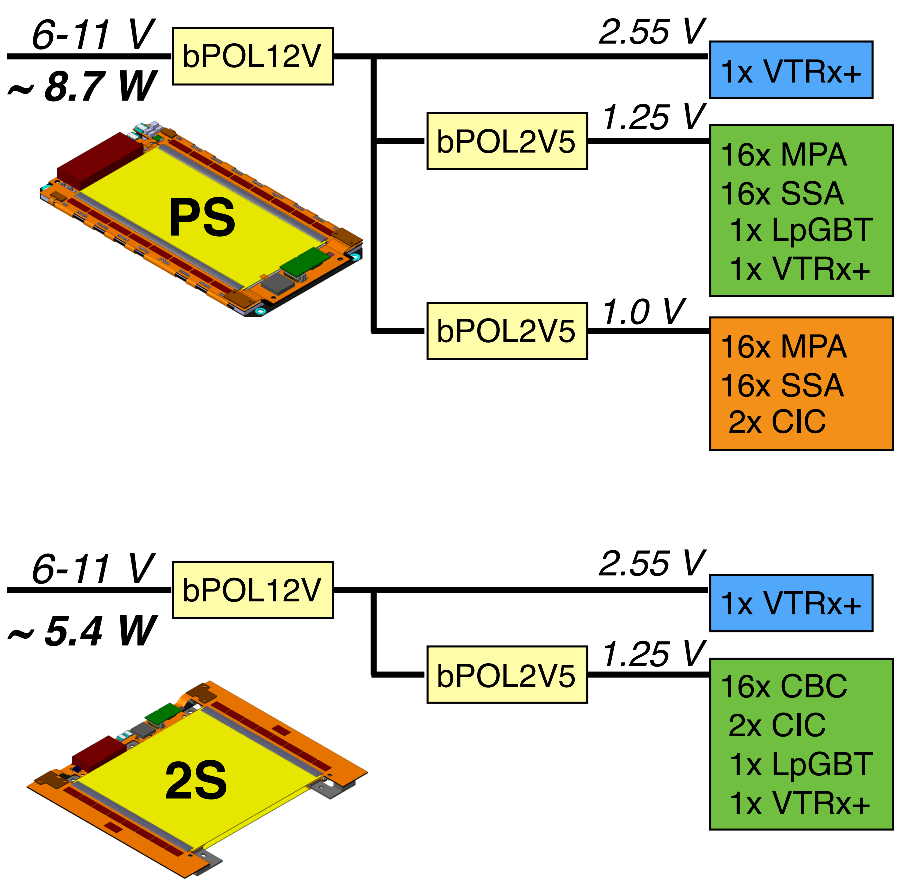
+

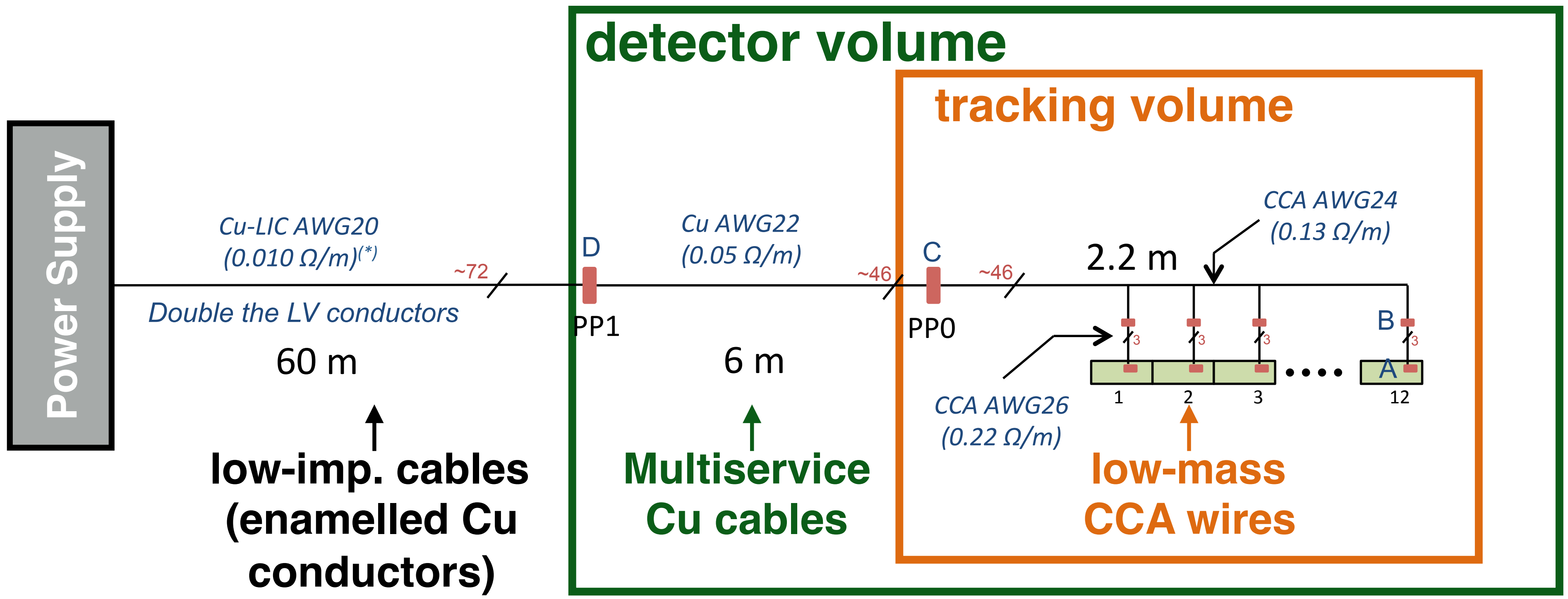
Powerful cooling system:

- (4+1) x 50kW cooling plants
- based on two-phase CO_2 cooling system (-30 ^{0}C set point)
- small pipes → low material budget

Outer Tracker Power Distribution

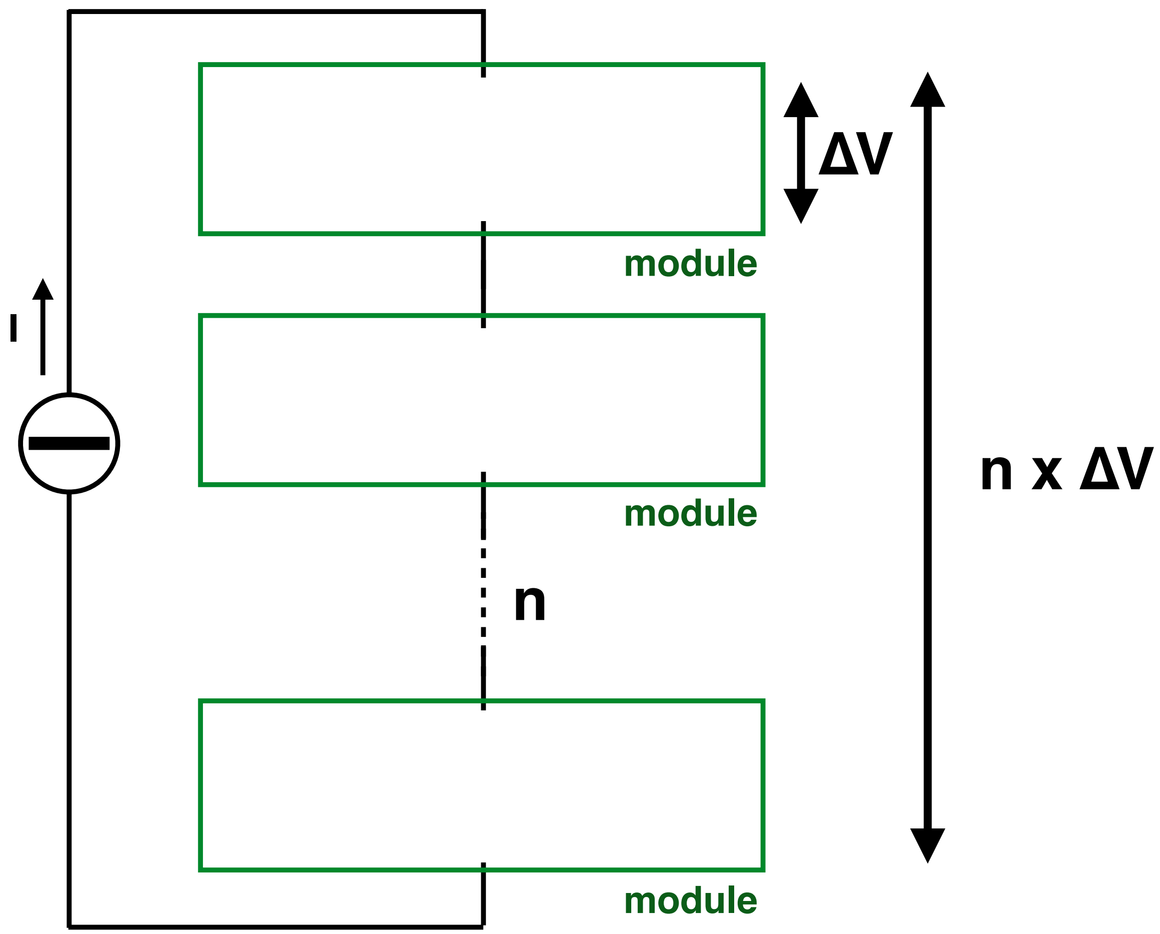


- Each module receives one LV and one HV line
- LV is converted on-module by DC/DC converters (bPOL12V, bPOL2V5)
- 13200 modules operated independently
- Power chain defined:
  - high-granularity power system
  - 12-channel modularity
  - low material budget in tracking region
  - low total resistivity essential
  - thorough study of mechanics and integration details.



IT: Serial Powering

Up to 12 modules connected in one serial chain



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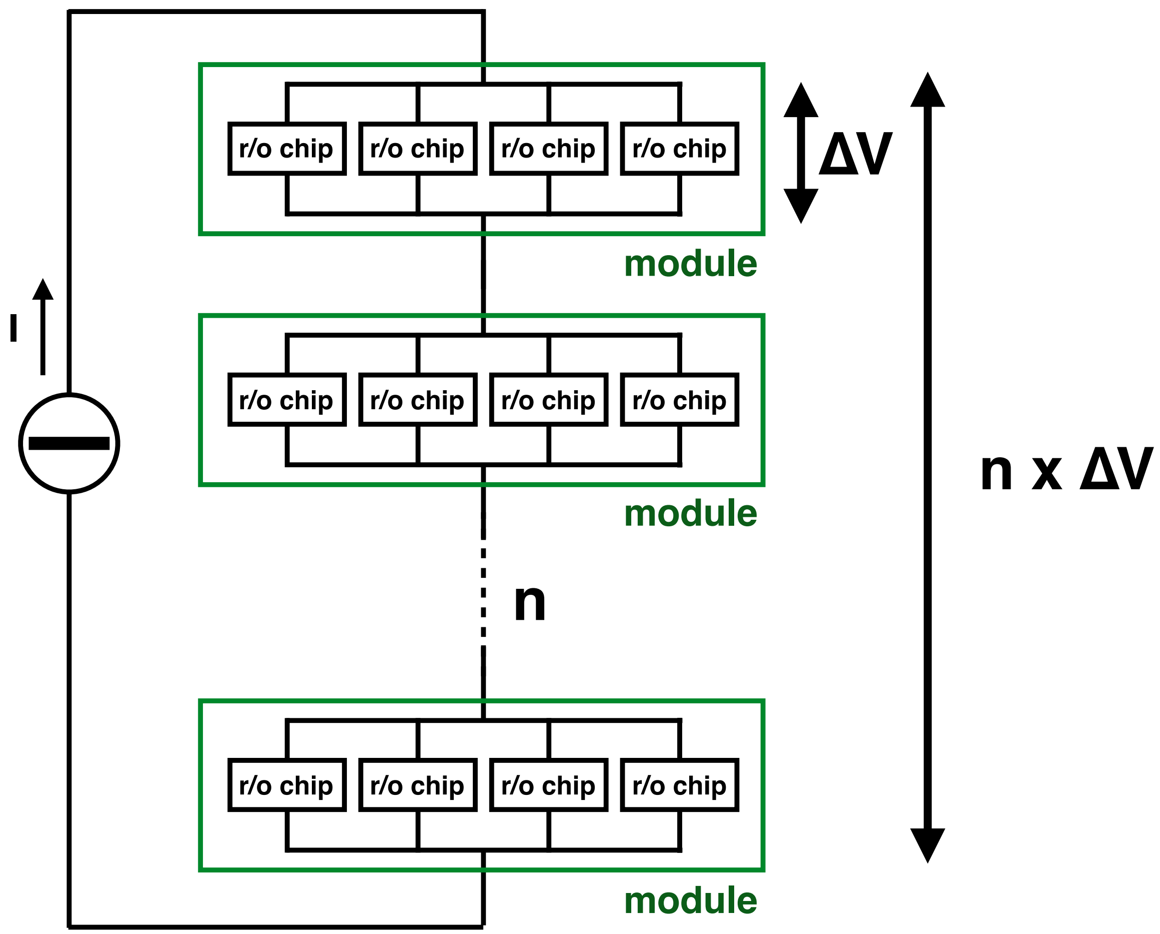
Current is shared in parallel b/w r/o chips inside the same module



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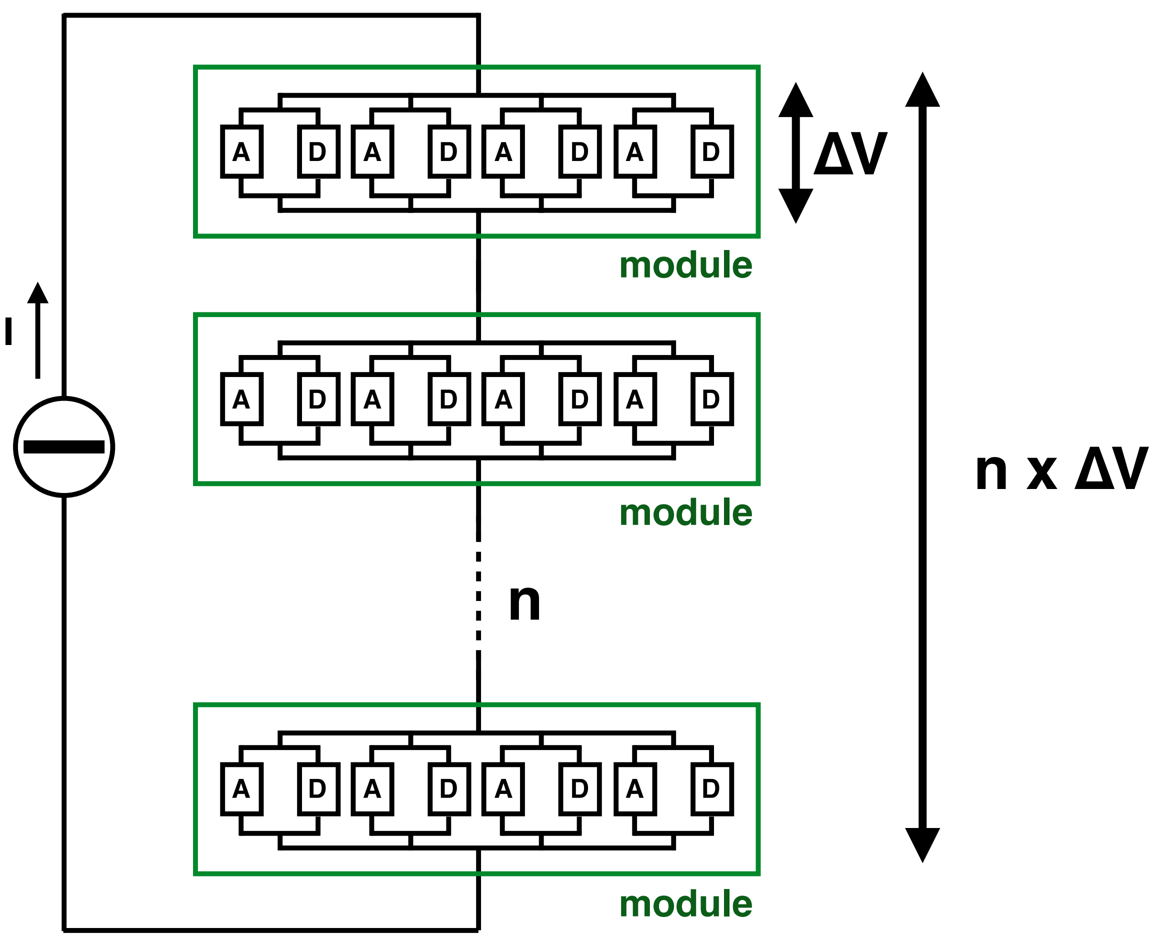

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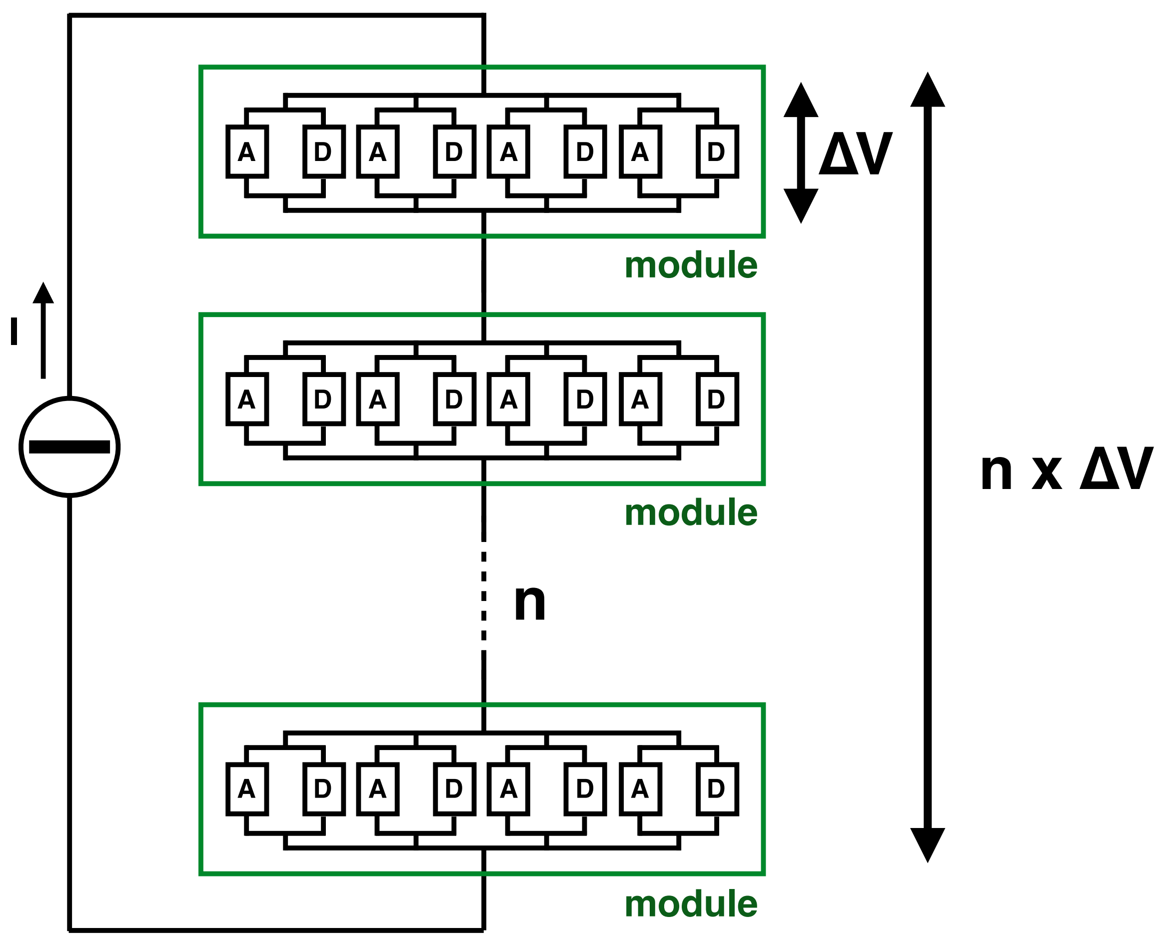
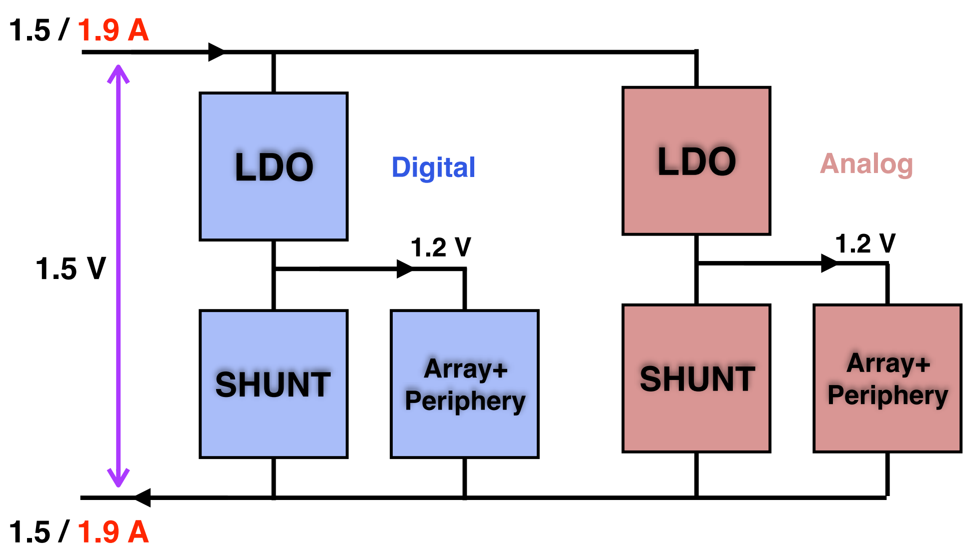


Serial powering is supported by the r/o chip via the shunt-LDO IP block, providing:

- ➡ shunt functionality: needed to implement the serial scheme
- ➡ LDO regulation: ensure correct voltage (~1.2V) to the electronics



- the Shunt-LDO configuration defines ΔV=f(I)
- aiming at ΔV~1.5 V (1.2V + 0.3V for LDO)
- the chain has to provide enough power for transients: considered ~ 25% current headroom w.r.t. “typical” conditions

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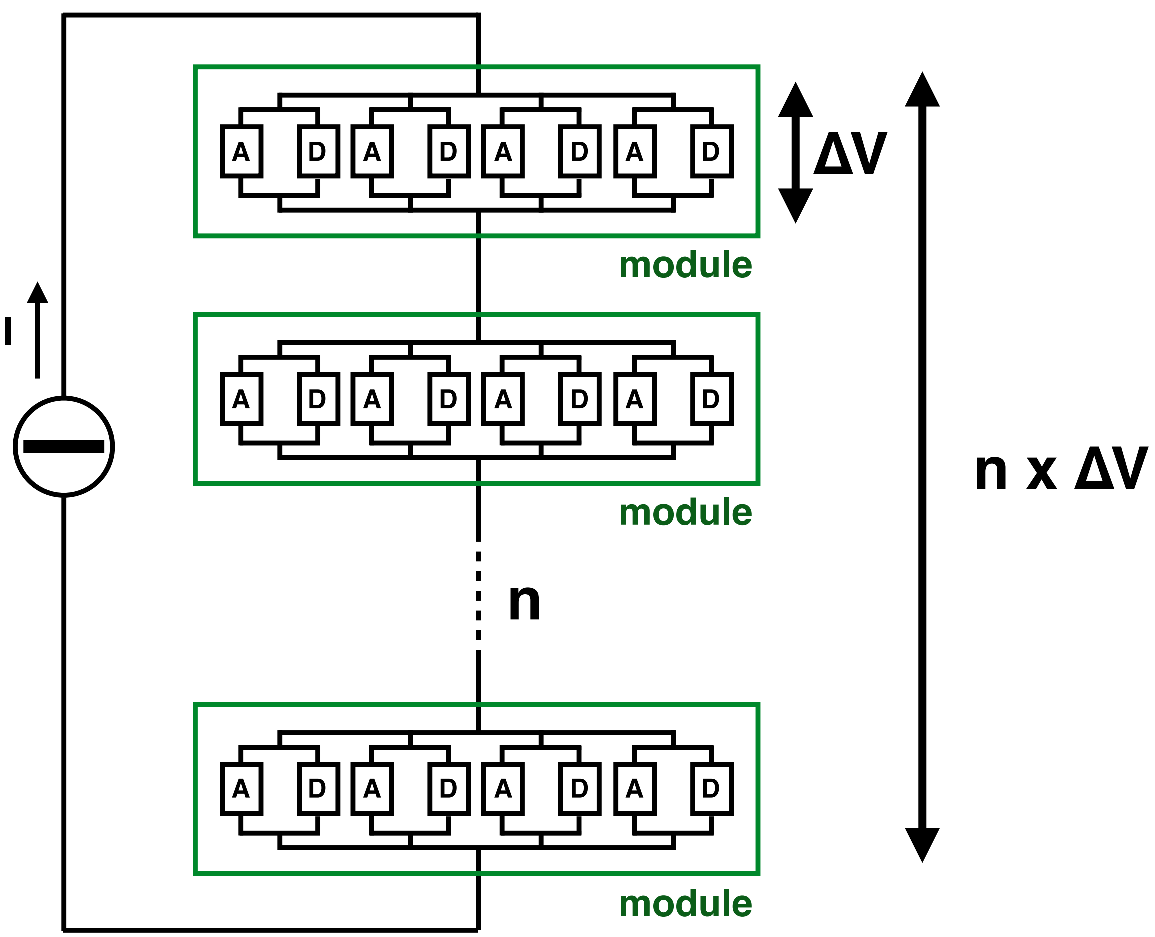

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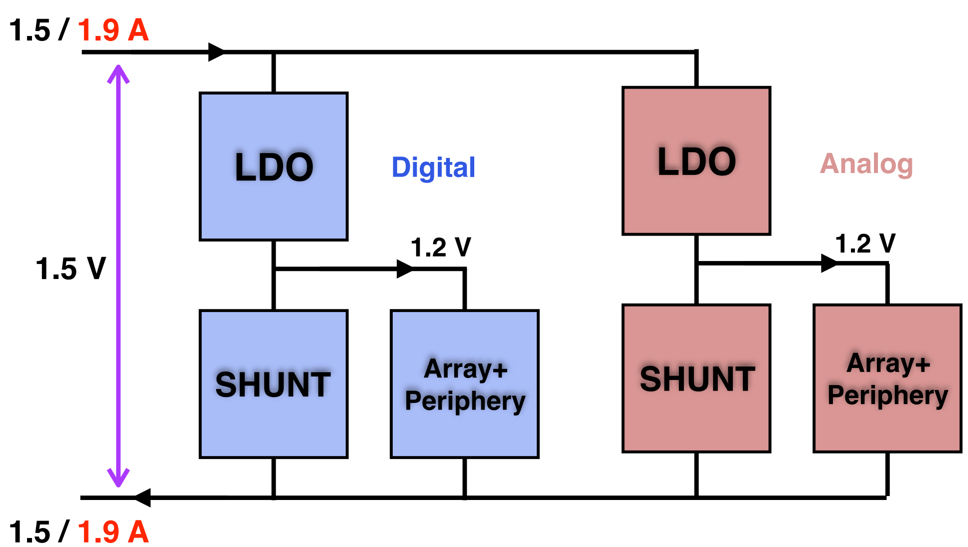

~ 500 serial chains power the full IT

4 A chains (2-chip modules)

8 A chains (4-chip modules)

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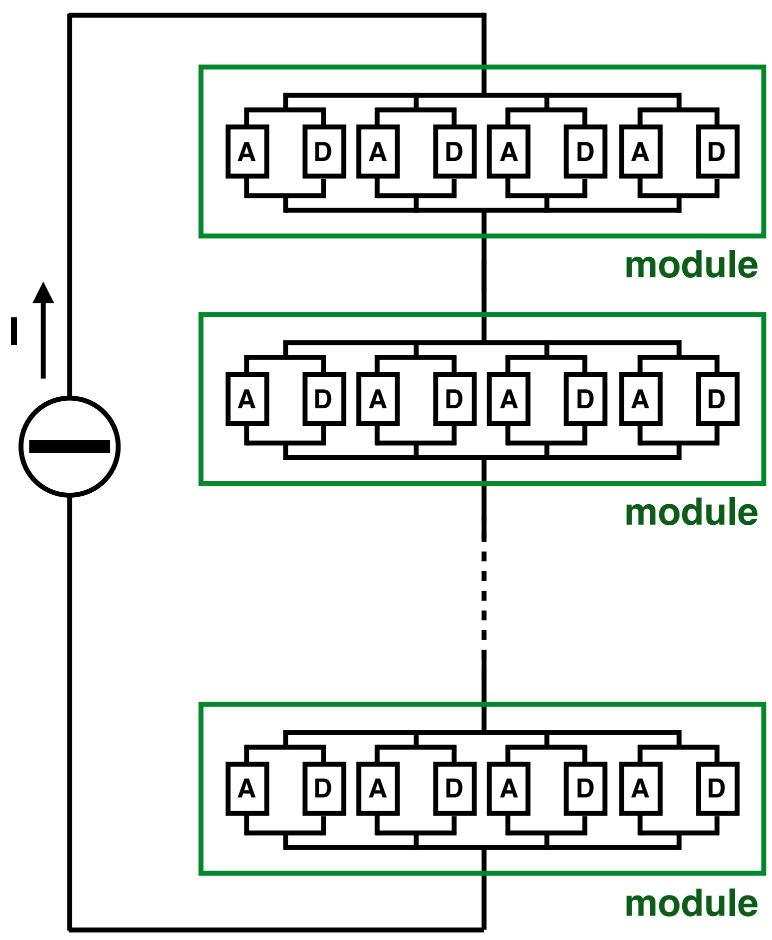

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Active R&D ongoing in ATLAS, CMS and RD53 with tests and simulations:

- Serial chain failure modes
- current sharing
- turn on procedure
- HV distribution in parallel to modules within the same serial chain
- Additional chip protection features under study

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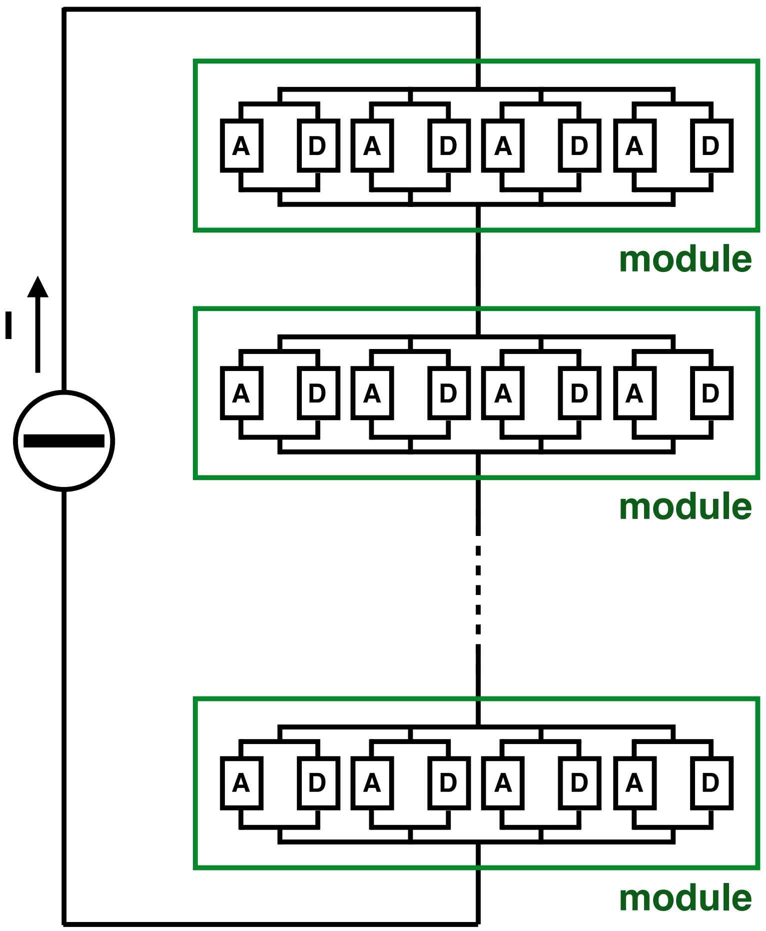

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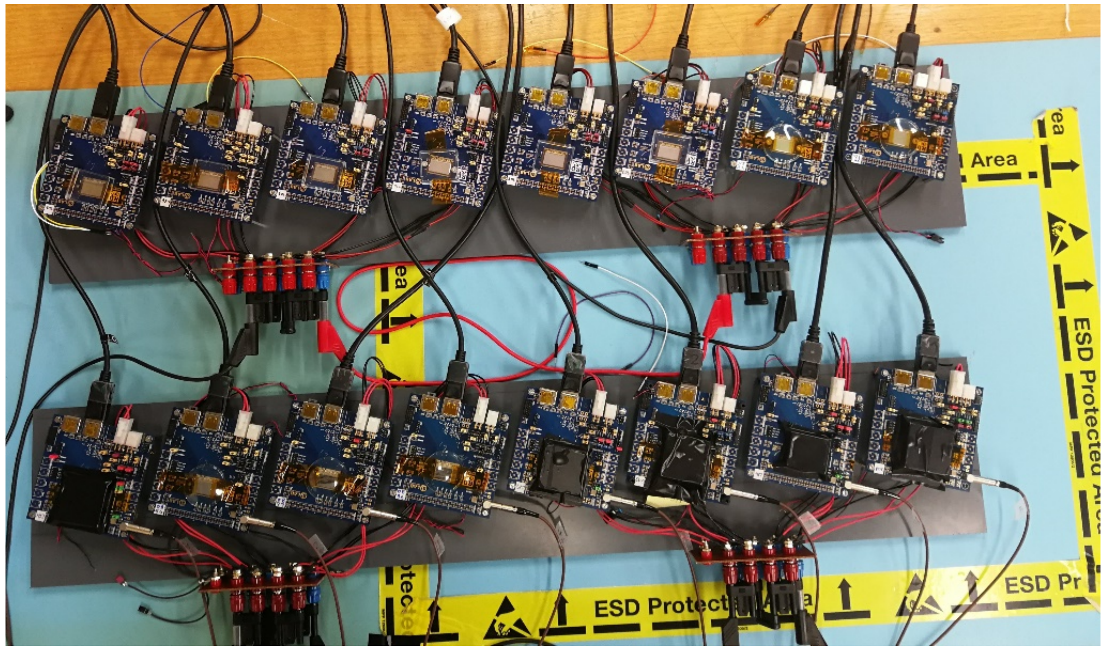


Serial chains with up to 16 RD53A chips were successfully operated in lab

~ 500 serial chains power the full IT

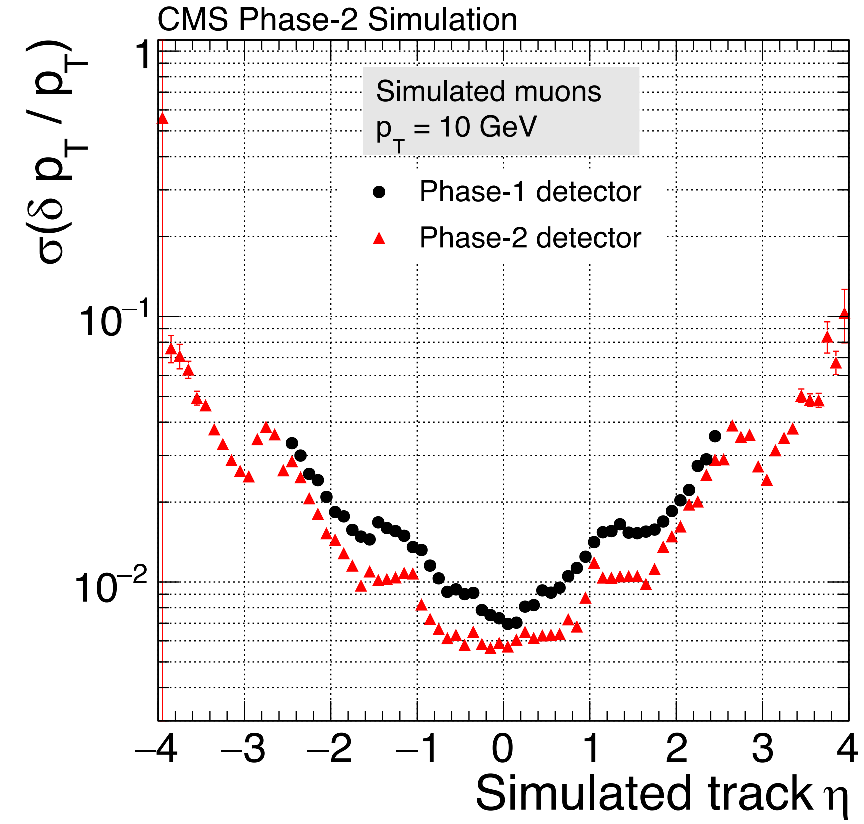
4 A chains (2-chip modules)

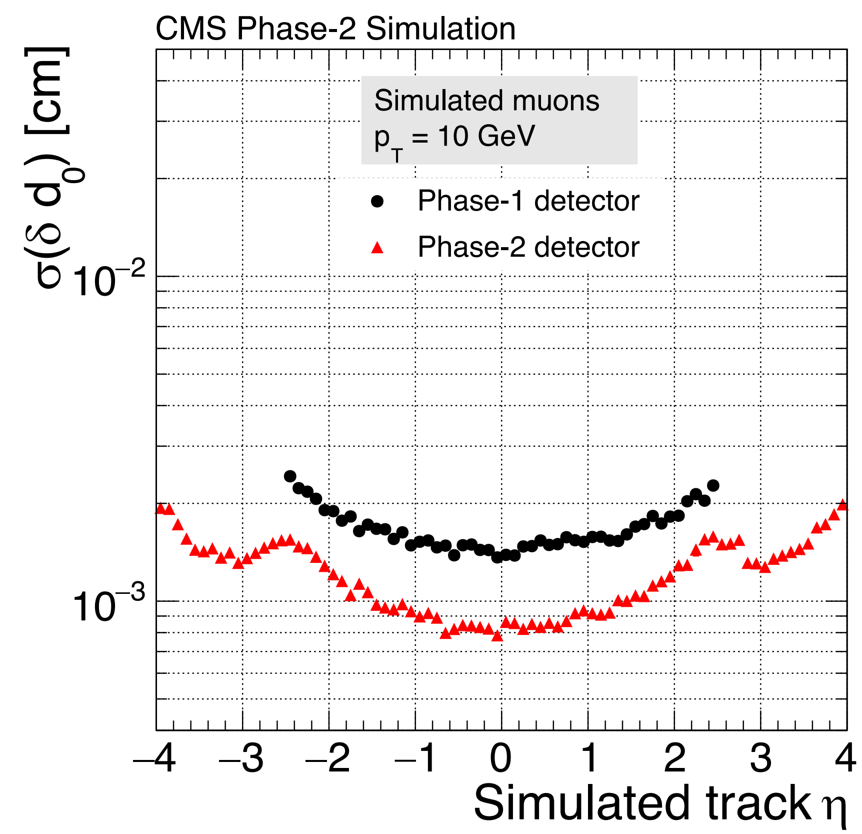
8 A chains (4-chip modules)

Serial Powering concept established

Summary

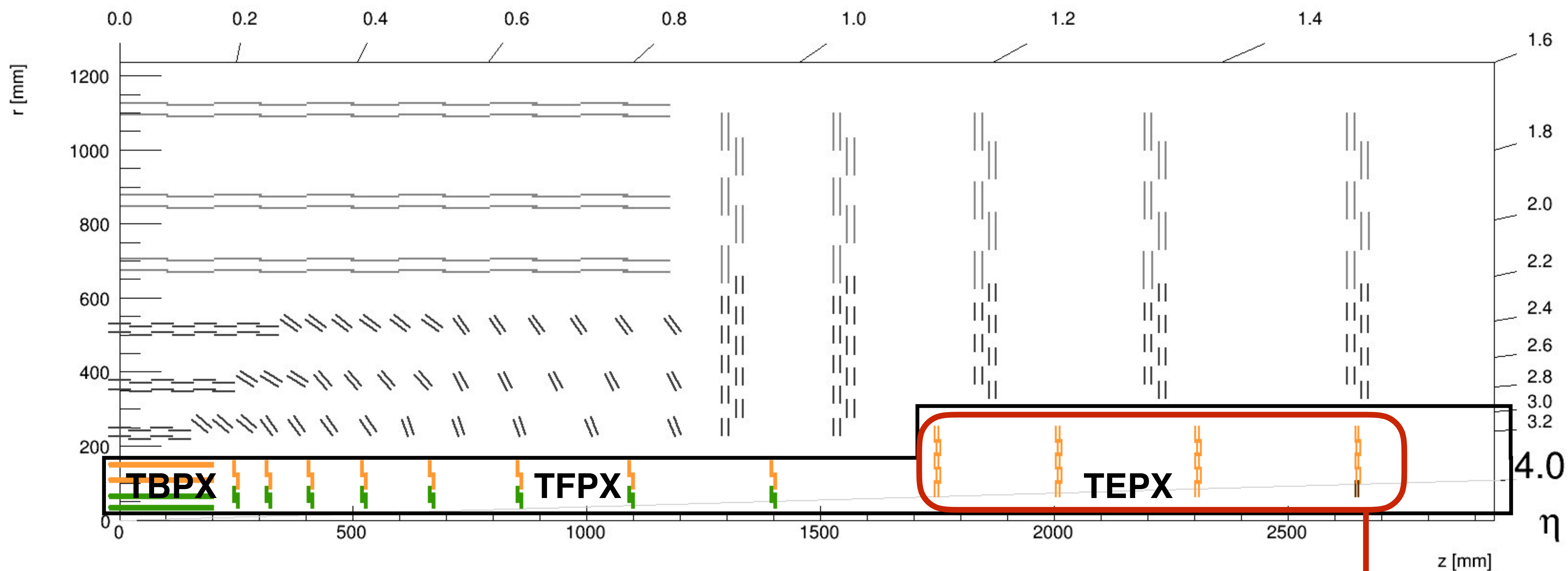
- The upgraded CMS tracker is going to be a radiation-hard highly segmented detector designed to operate in the harsh HL-LHC environment and to provide:
  - excellent tracking performance
  - extended η coverage and luminosity measurement
  - L1 trigger primitives @ 40MHz
- The performance is resting on top of innovative modular, lightweight design choices and new technologies:
  - new rad-hard ASICs and optical links
  - rad-hard thin silicon sensors
  - innovative powering schemes
  - CO_2 cooling
- Mechanical layout and integration studies are advanced
- Final ASICs prototype submissions expected by 2020
- First module prototypes in 2020
- Way paved towards the new tracker operating inside CMS in 2026





Reserve

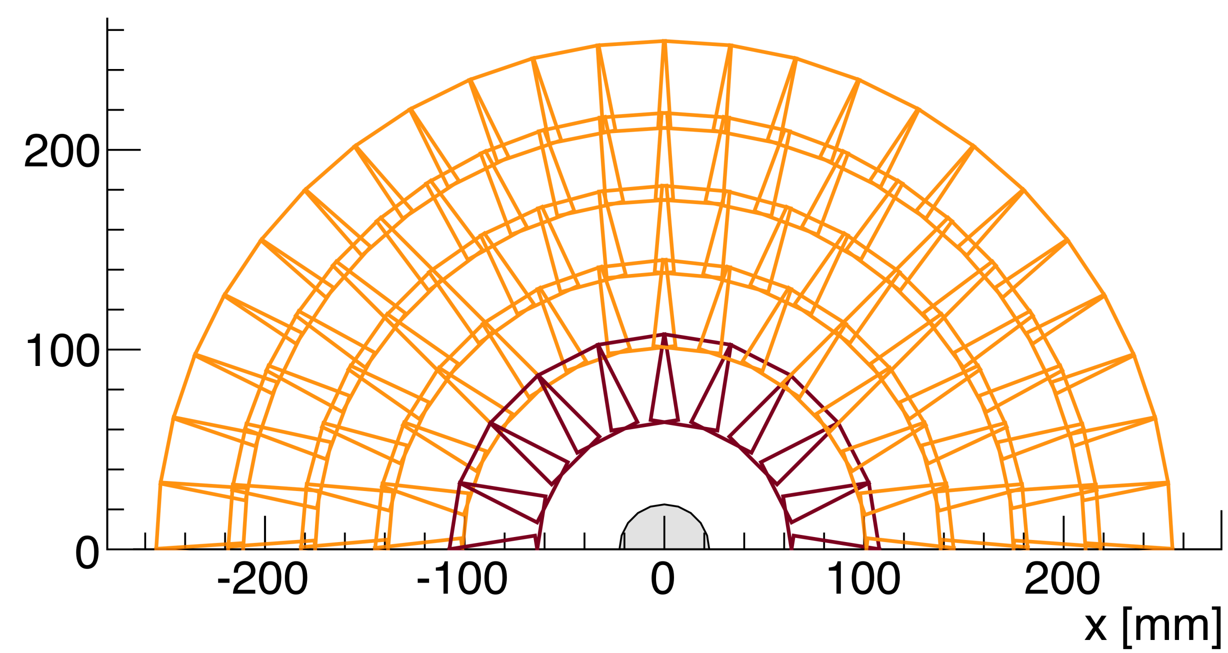
The Inner Tracker

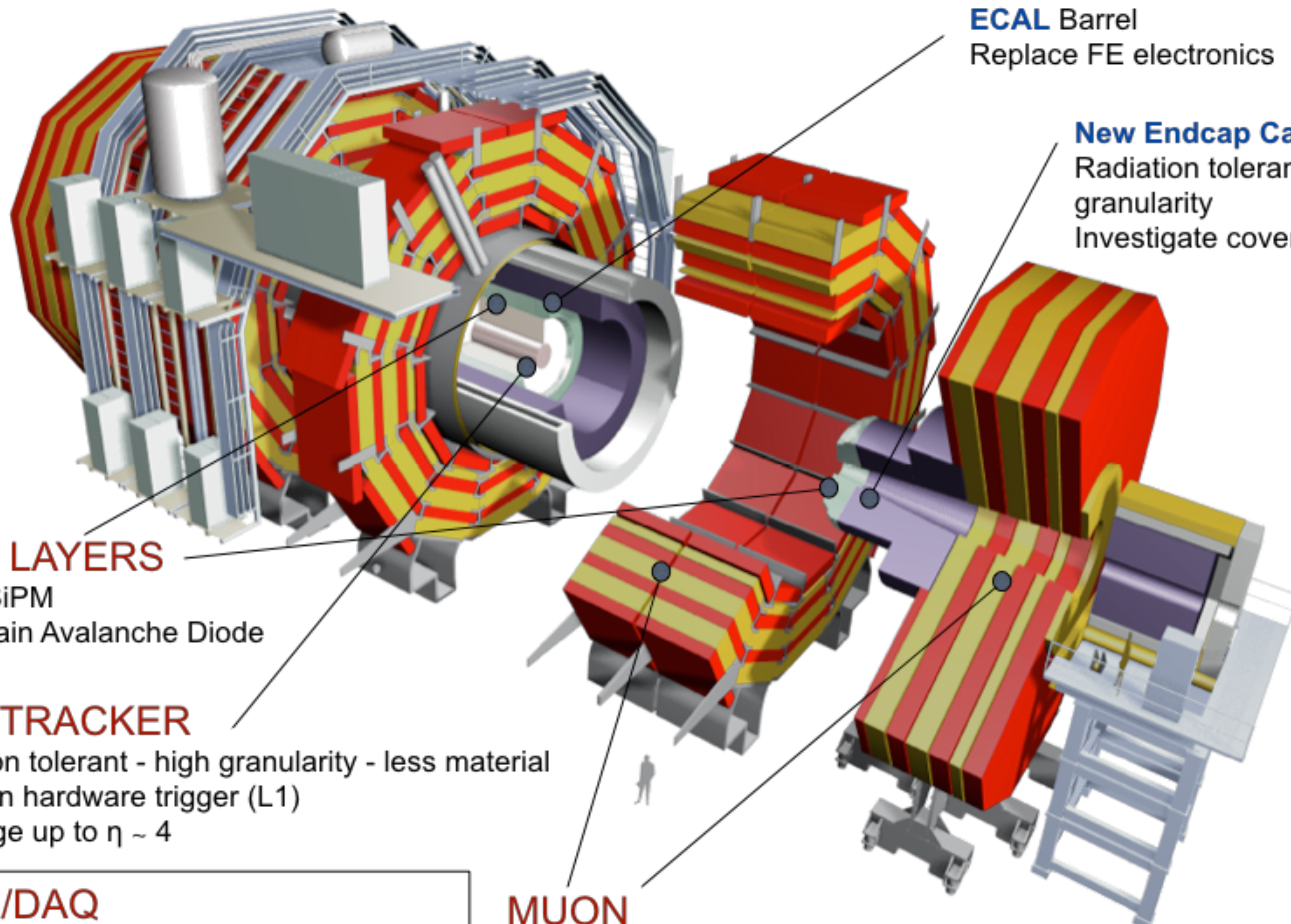


TEPX is a large and powerful luminometer:

- it receives 75 kHz extra lumi triggers (up to 10MHz full bandwidth when no data taking)
- lumi is measured via cluster counting, multihit stub counting, track counting, …

First ring of the last disk is fully dedicated to background monitoring, with separate readout and control





CALORIMETERS

ECAL Barrel
Replace FE electronics

New Endcap Calorimeters
Radiation tolerant - high granularity
Investigate coverage up to $\eta \sim 4$

MIP TIMING LAYERS

Barrel: LYSO + SiPM
Endcaps: Low Gain Avalanche Diode

NEW TRACKER

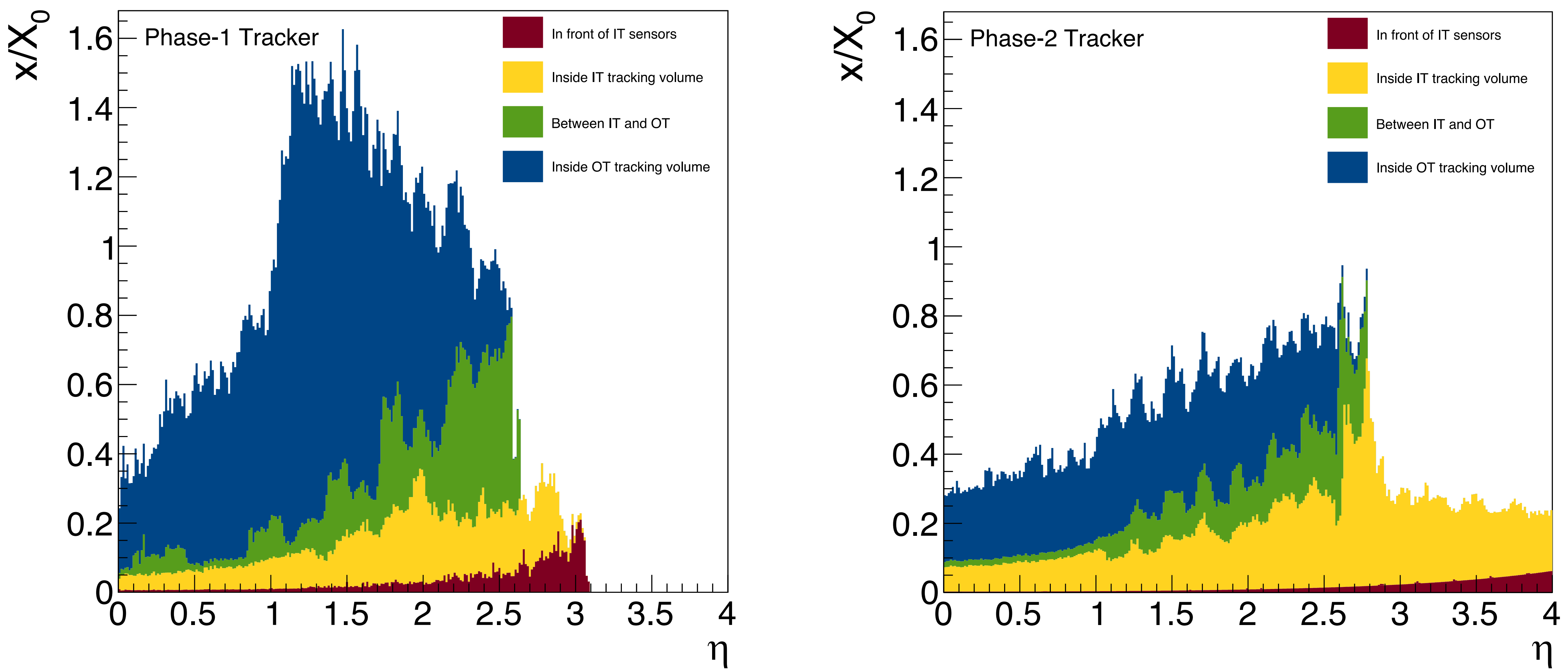
Radiation tolerant - high granularity - less material
Tracks in hardware trigger (L1)
Coverage up to $\eta \sim 4$

TRIGGER/DAQ

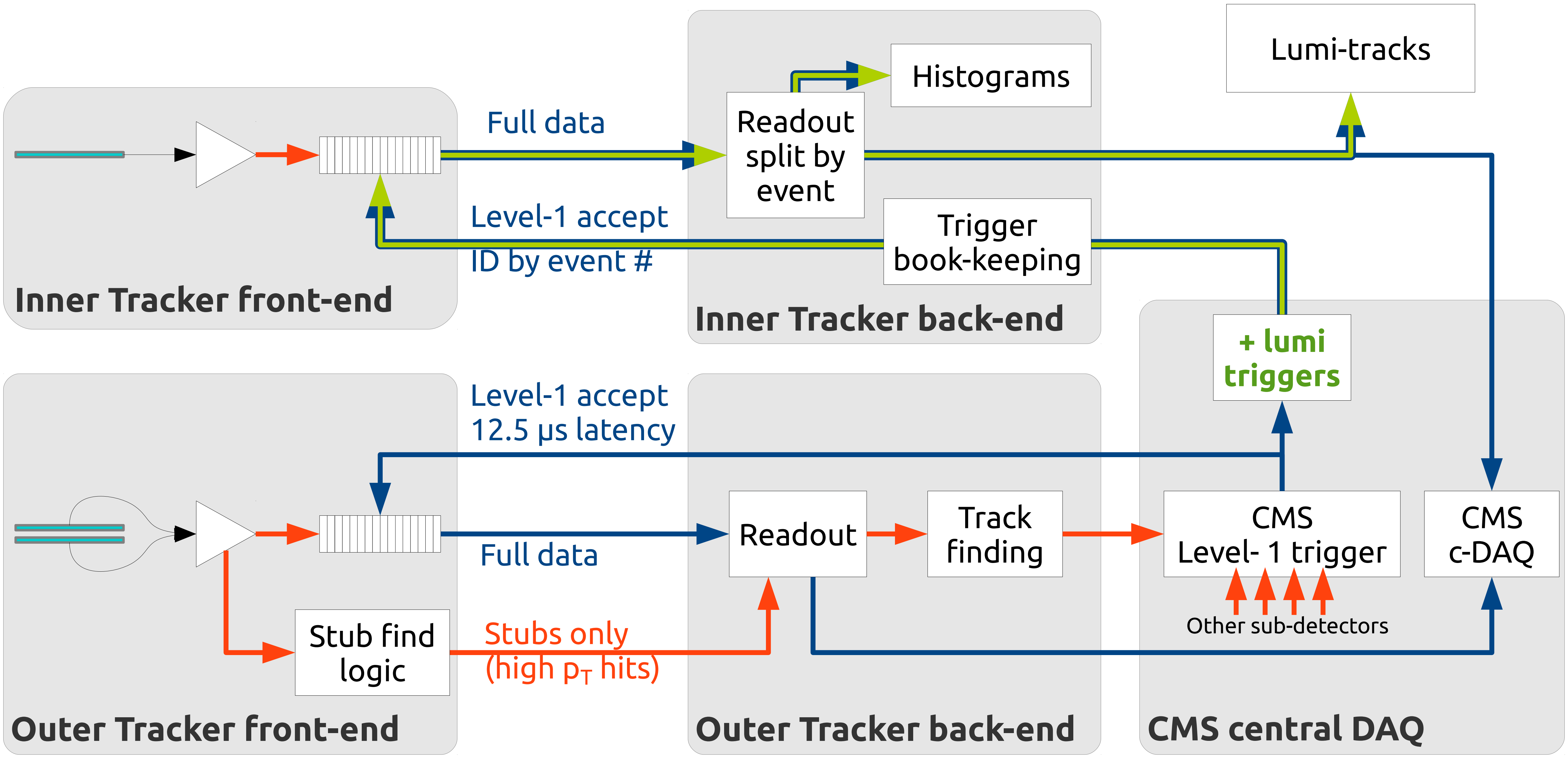
L1 (hardware) with tracks and rate ~750kHz
Latency ≥ 10 μs
HLT output up to 10 kHz

MUON

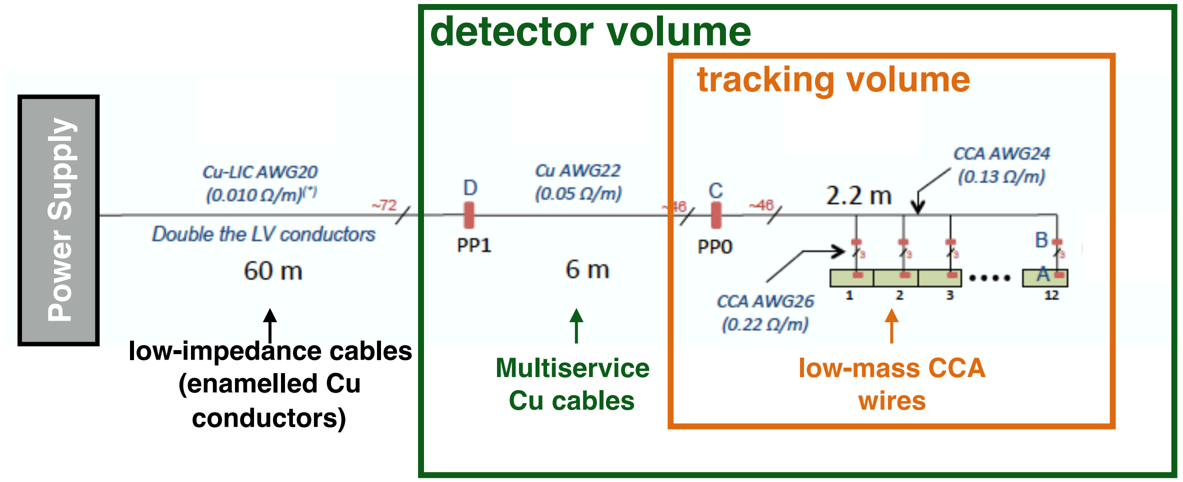
Replace DT FE electronics
Complete RPC coverage in forward region (new GEM/RPC technology)
Investigate Muon-tagging up to $\eta \sim 4$



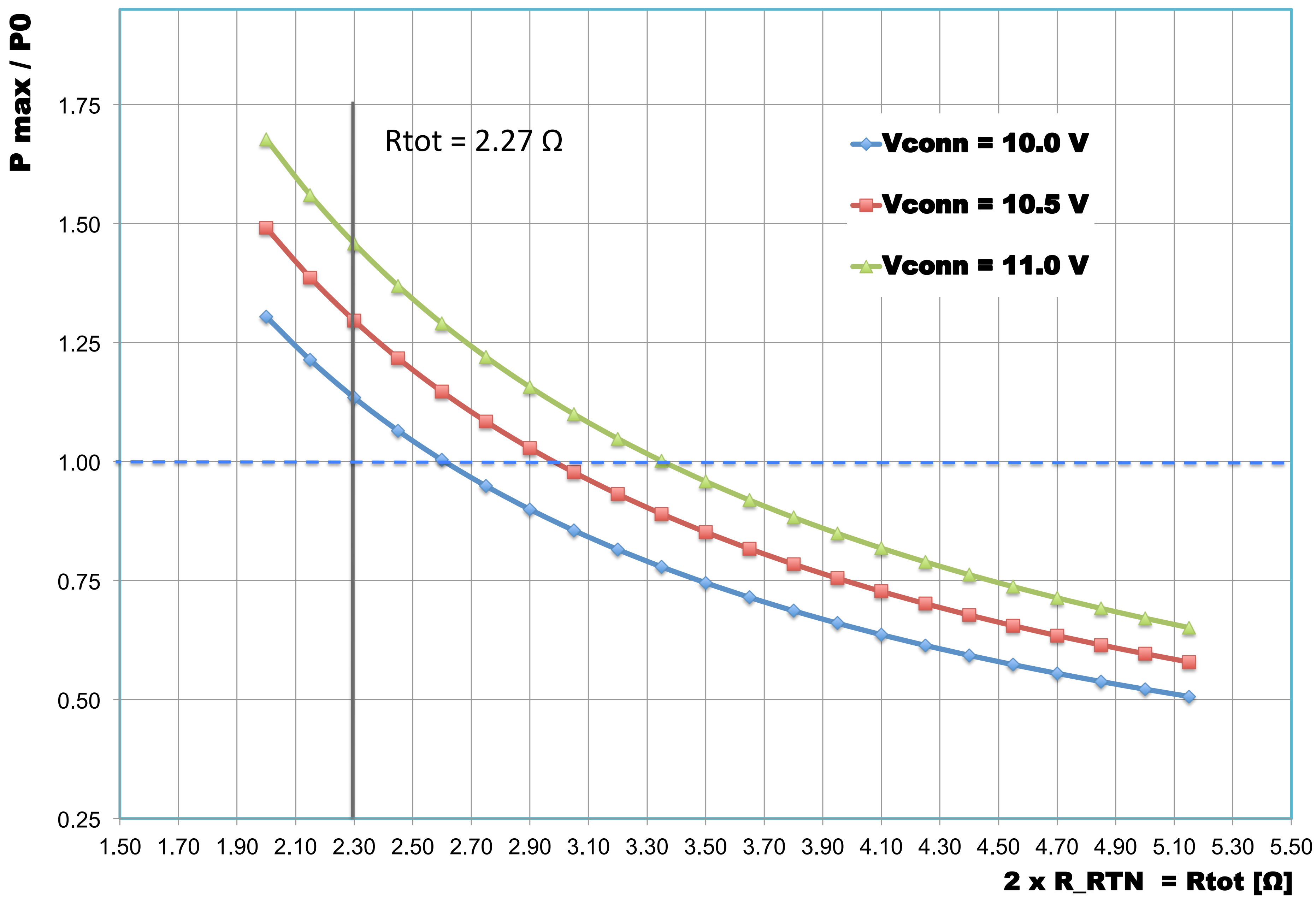
Phase-1 Tracker
Phase-2 Tracker
In front of IT sensors
Inside IT tracking volume
Between IT and OT
Inside OT tracking volume
x/X_0
η

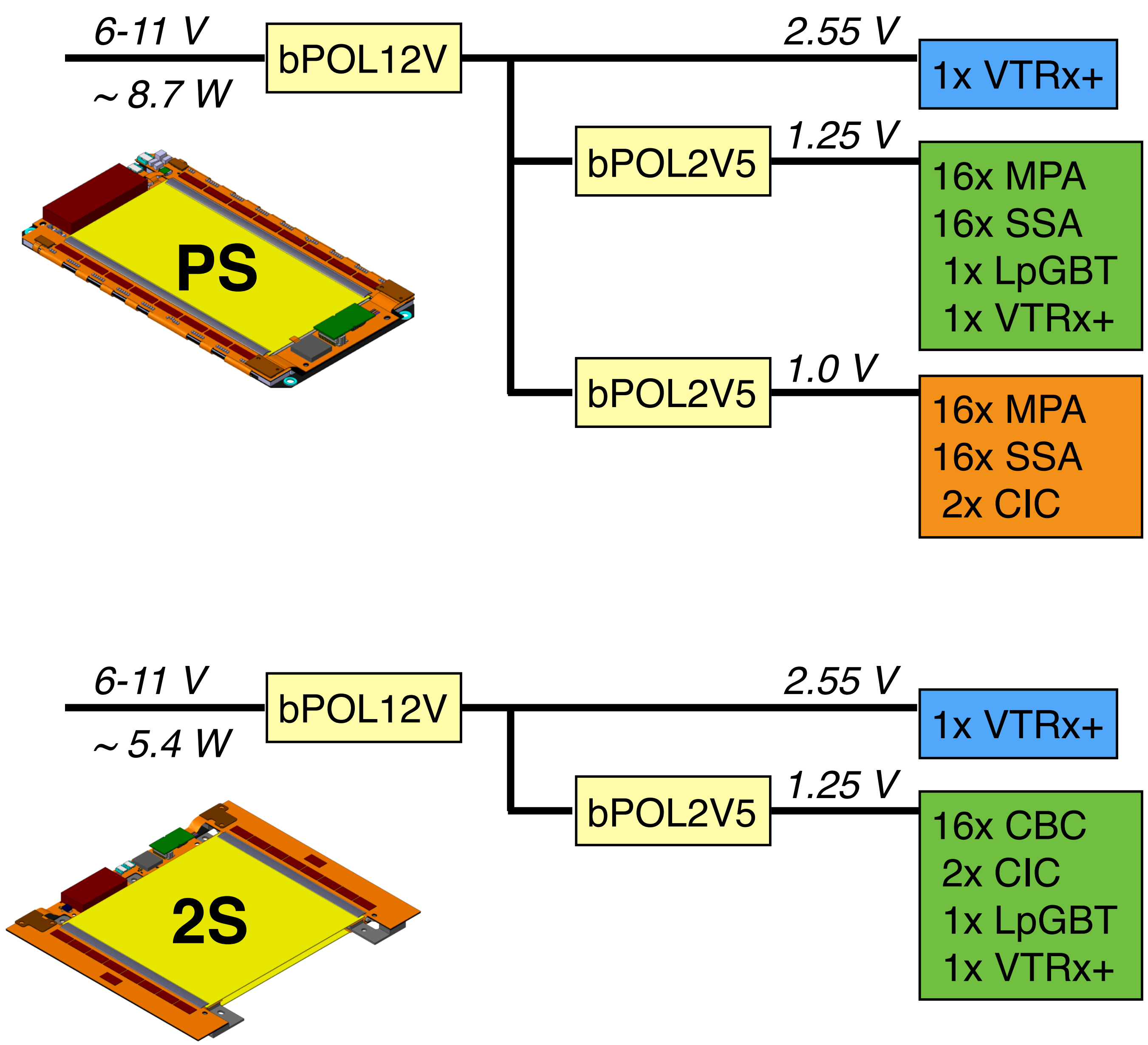


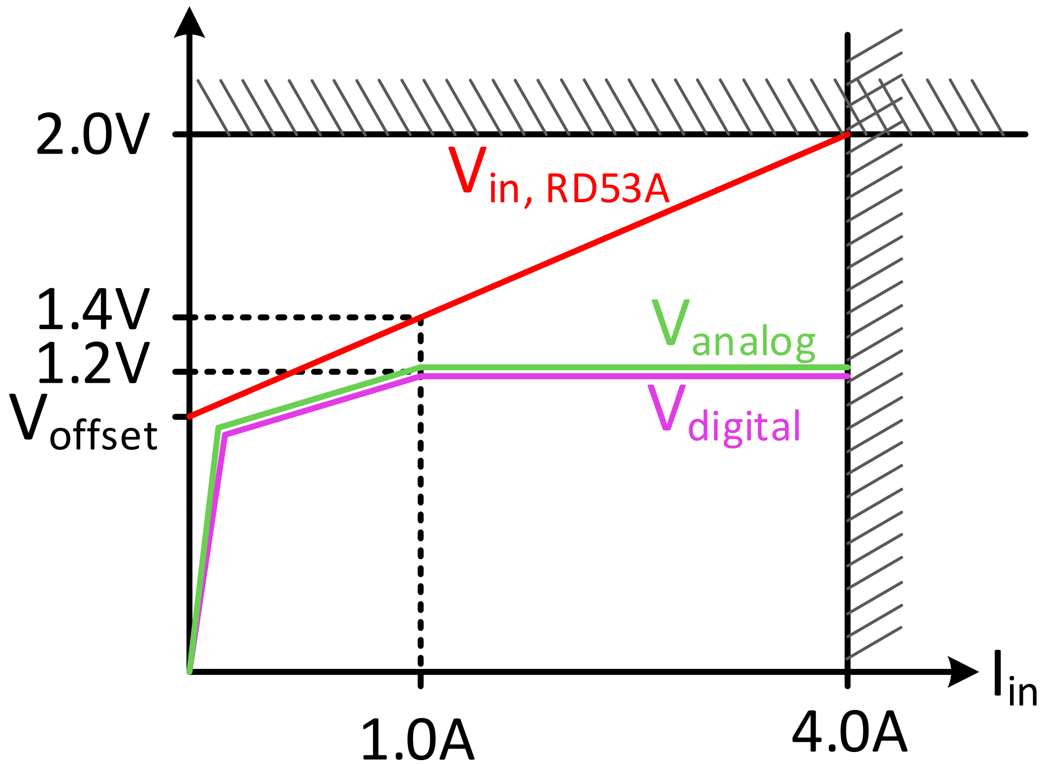
40 MHz – Real time **750 kHz** – CMS Level-1 trigger **~75 kHz** – Lumi-specific trigger


detector volume
tracking volume
Power Supply
Cu-LIC AWG20
Double the LV conductors
60 m
low-impedance cables (enamelled Cu conductors)
D
PP1
Cu AWG22
6 m
Multiservice Cu cables
C
PP0
2.2 m
CCA AWG24
CCA AWG26
low-mass CCA wires

P0 = 8.7W


P max / P0
Rtot = 2.27 Ω
Vconn = 10.0 V
Vconn = 10.5 V
Vconn = 11.0 V
1.75
1.50
1.25
1.00
0.75
0.50
0.25
1.50 1.70 1.90 2.10 2.30 2.50 2.70 2.90 3.10 3.30 3.50 3.70 3.90 4.10 4.30 4.50 4.70 4.90 5.10 5.30 5.50
2 x R_RTN = Rtot [Ω]

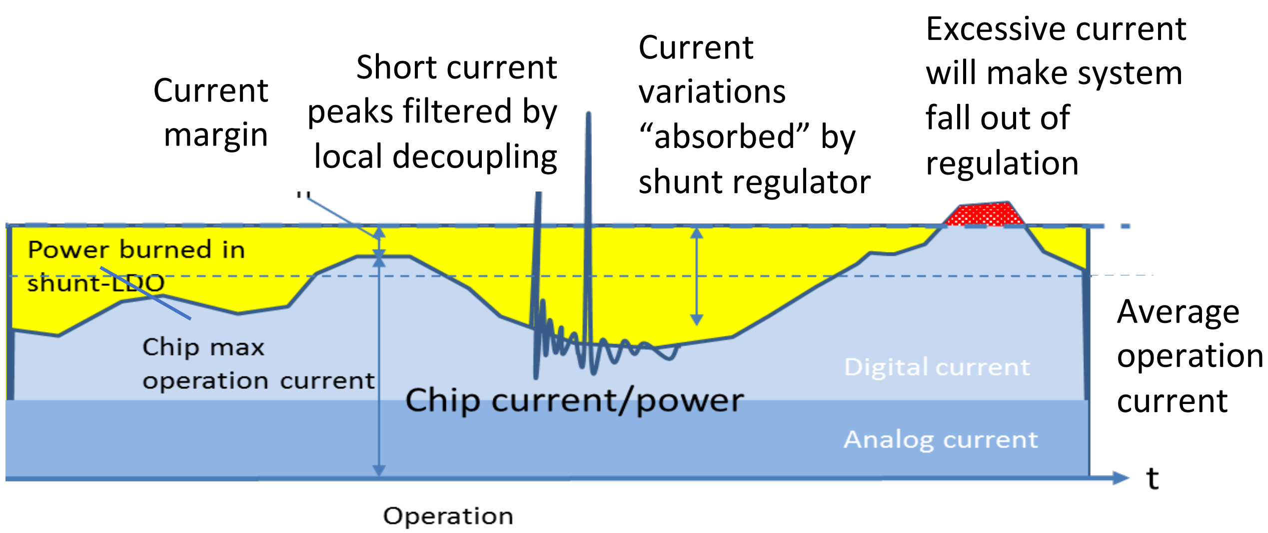

6-11 V
~ 8.7 W
bPOL12V
2.55 V
1x VTRx+
bPOL2V5
1.25 V
16x MPA
16x SSA
1x LpGBT
1x VTRx+
bPOL2V5
1.0 V
16x MPA
16x SSA
2x CIC
PS
6-11 V
~ 5.4 W
bPOL12V
2.55 V
1x VTRx+
bPOL2V5
1.25 V
16x CBC
2x CIC
1x LpGBT
1x VTRx+
2S

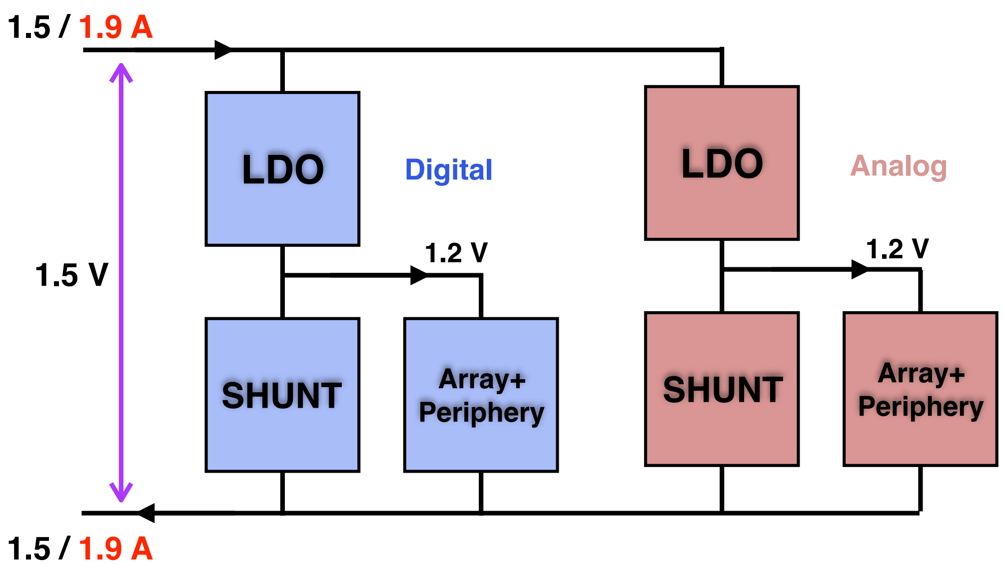


Serial Power chains are current driven:

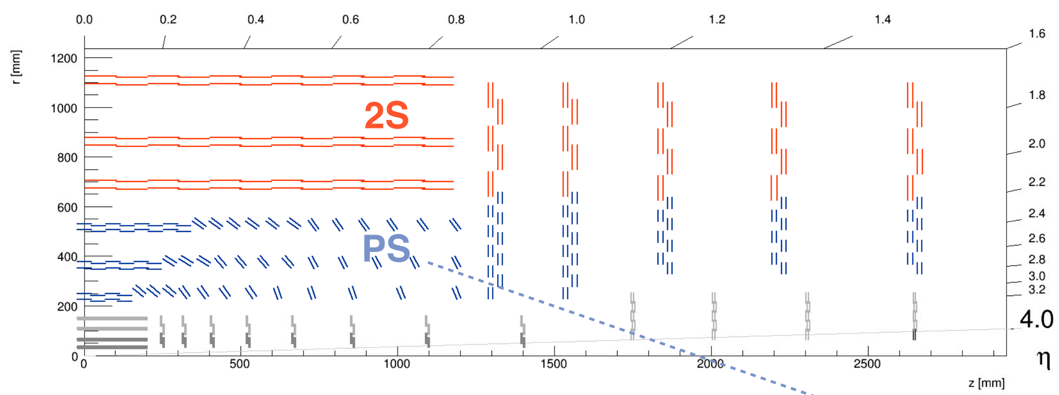
- the Shunt-LDO configuration defines ΔV=f(I)
- aiming at ΔV~1.5 V (1.2V + 0.3V for LDO)
- the chain has to provide enough power for transients: considering ~ 25% current headroom w.r.t. "typical" conditions

→ serial powering is intrinsically not efficient





Two basic types of OT Modules



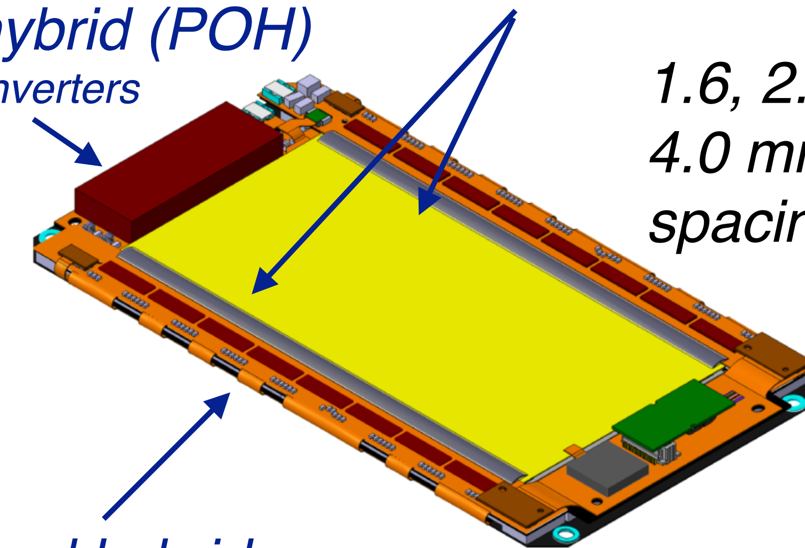
Macro Pixel-Strip (PS) modules:

45 cm² active area:

- *2 × 960 Strips 2.5 cm × 100 μm*
- *32 ×960 macro-pixels 1.5 mm × 100 μm*

power hybrid (POH)
DC/DC converters

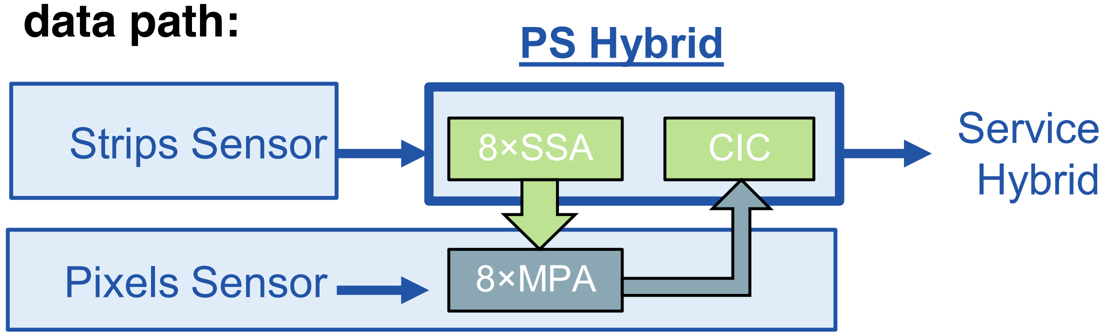
1.6, 2.6 or 4.0 mm spacing



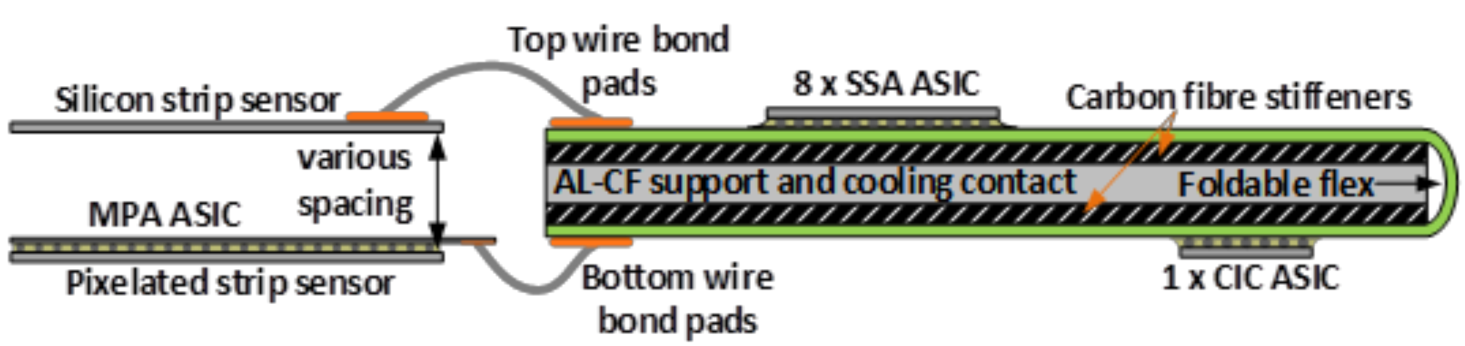
front-end hybrids:
8 SSA readout ASICs
1 Concentrator (CIC) ASIC

readout hybrid (ROH)
lpGBT + opto module

data path:



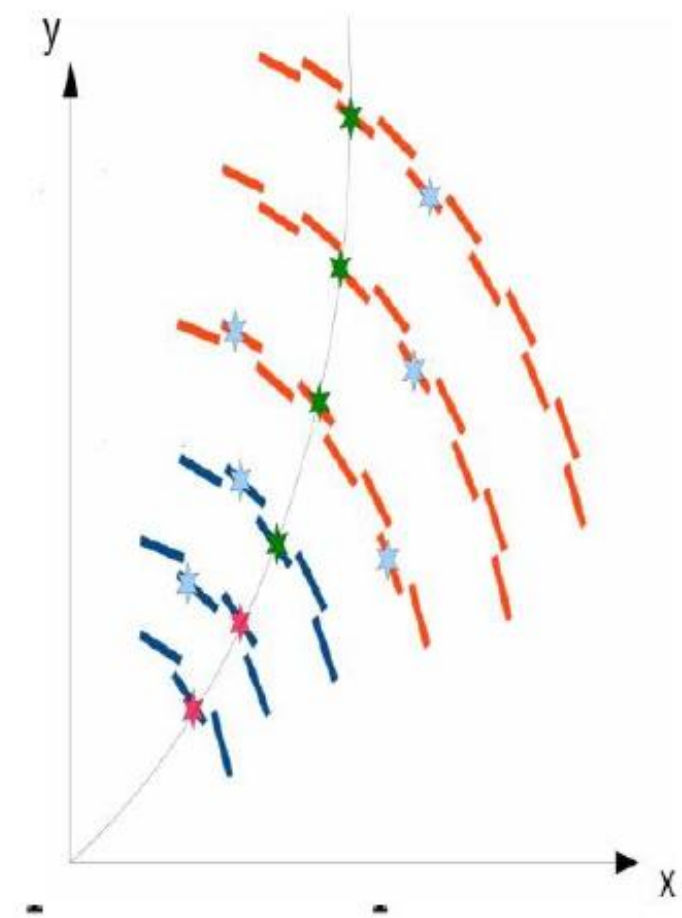
SSA = Short Strip ASIC → readout of short strip sensors
MPA = Macro Pixel ASIC → readout of Macro Pixel sensors



Tracking at L1 trigger level (5 μs latency)

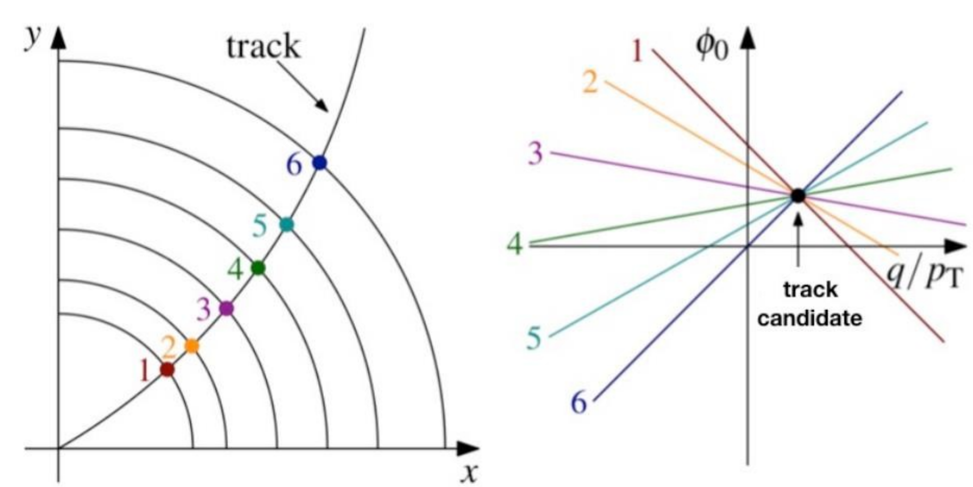
Pattern recognition:

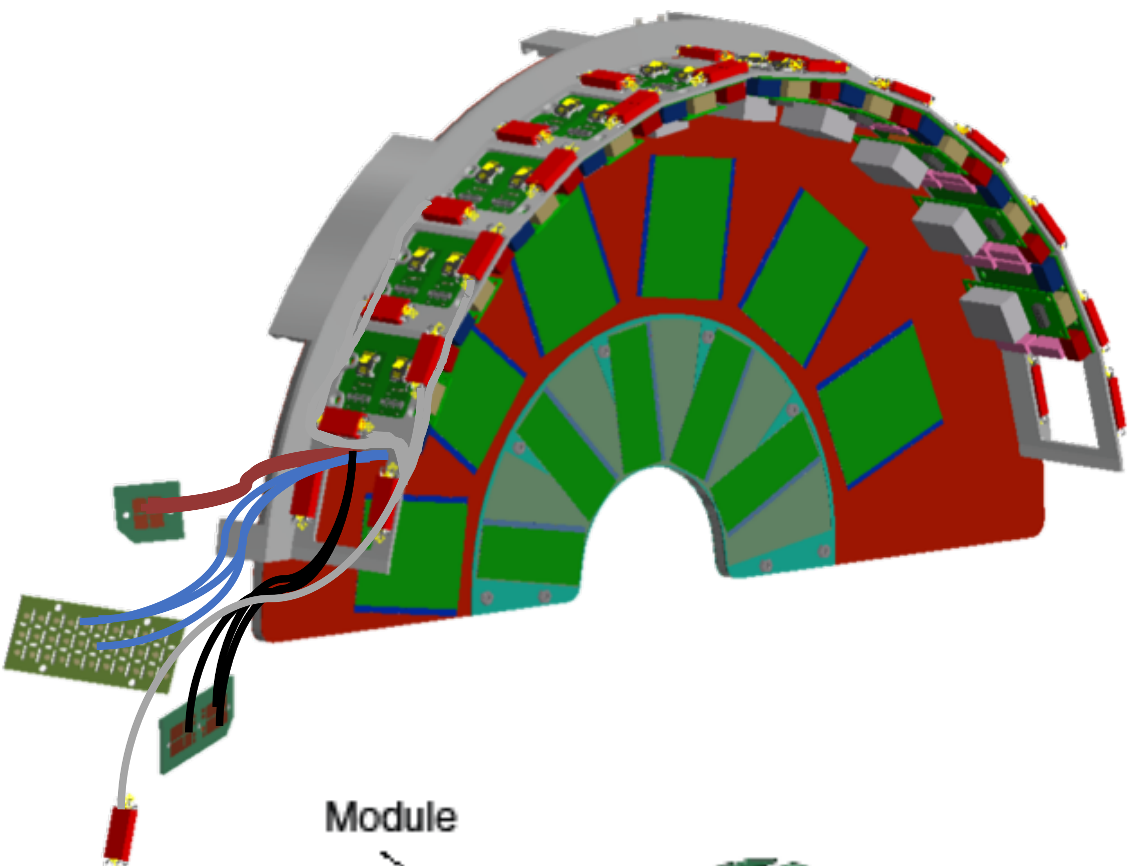
- **Tracklet approach**:
  - stubs in adjacent layers → "Tracklets"
- **Hough Transformation approach**:
  - Select track candidate through Hough Transform

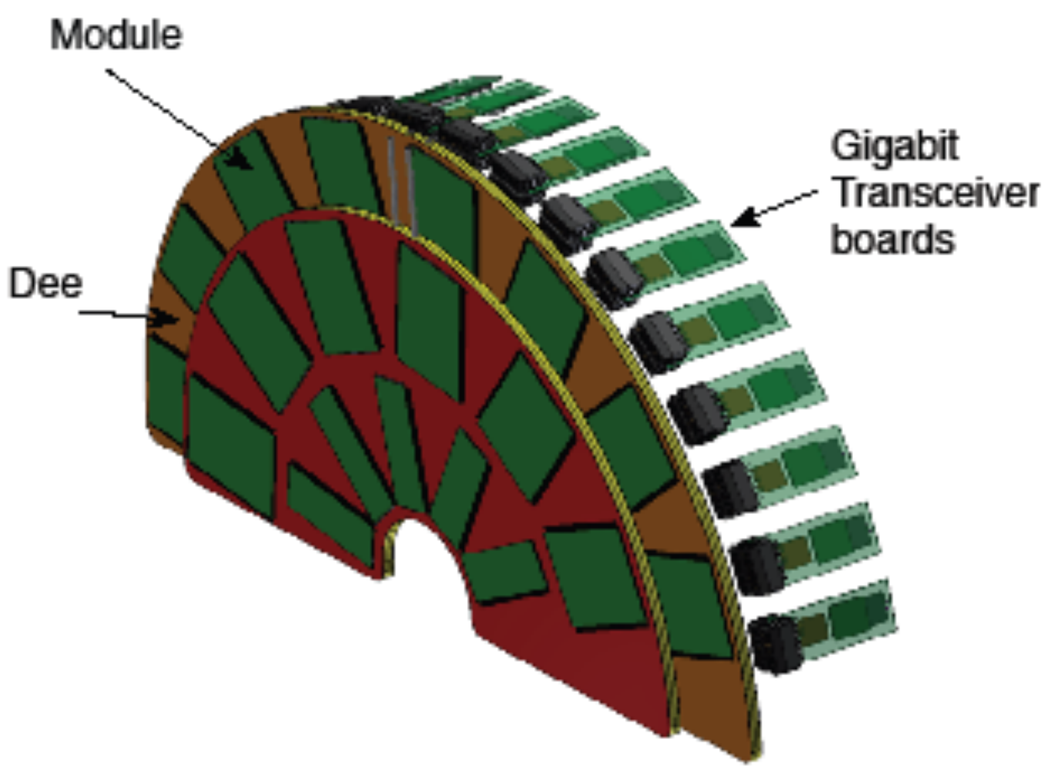


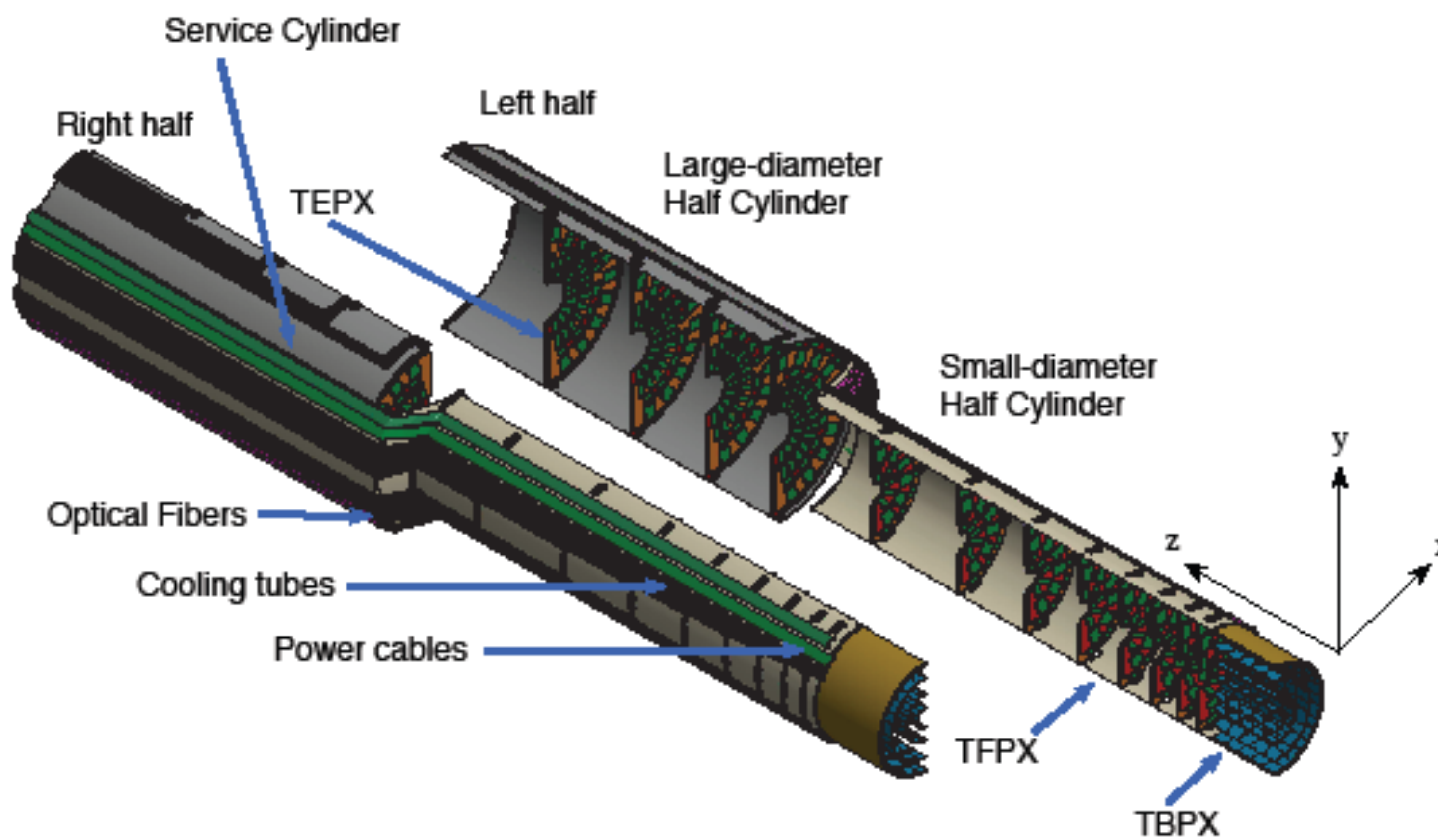
track fitting:

- Minimize chi2 (Kalman Filter)
- Remove duplicate






Module
Gigabit
Transceiver
boards
Dee


Service Cylinder
Right half
Left half
TEPX
Large-diameter
Half Cylinder
Small-diameter
Half Cylinder
Optical Fibers
Cooling tubes
Power cables
TFPX
TBPX
y
z
x