THE PHASE-2 UPGRADE OF THE CMS INNER TRACKER

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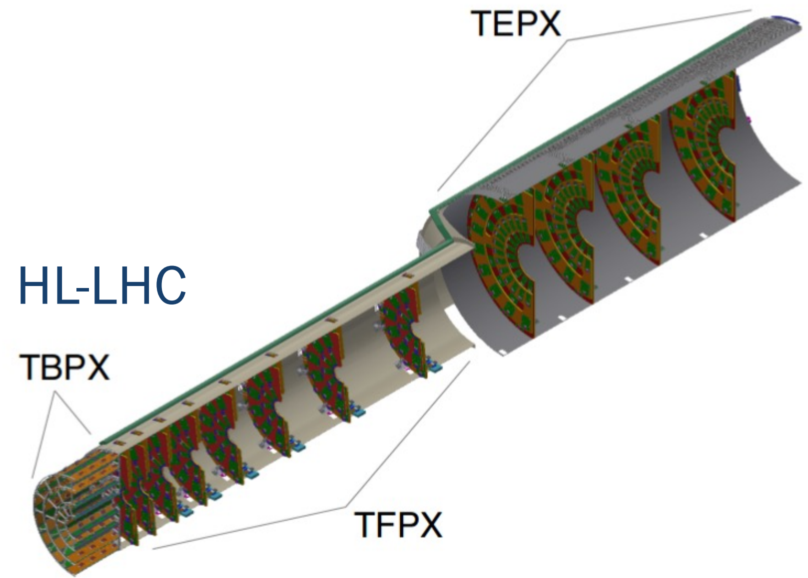
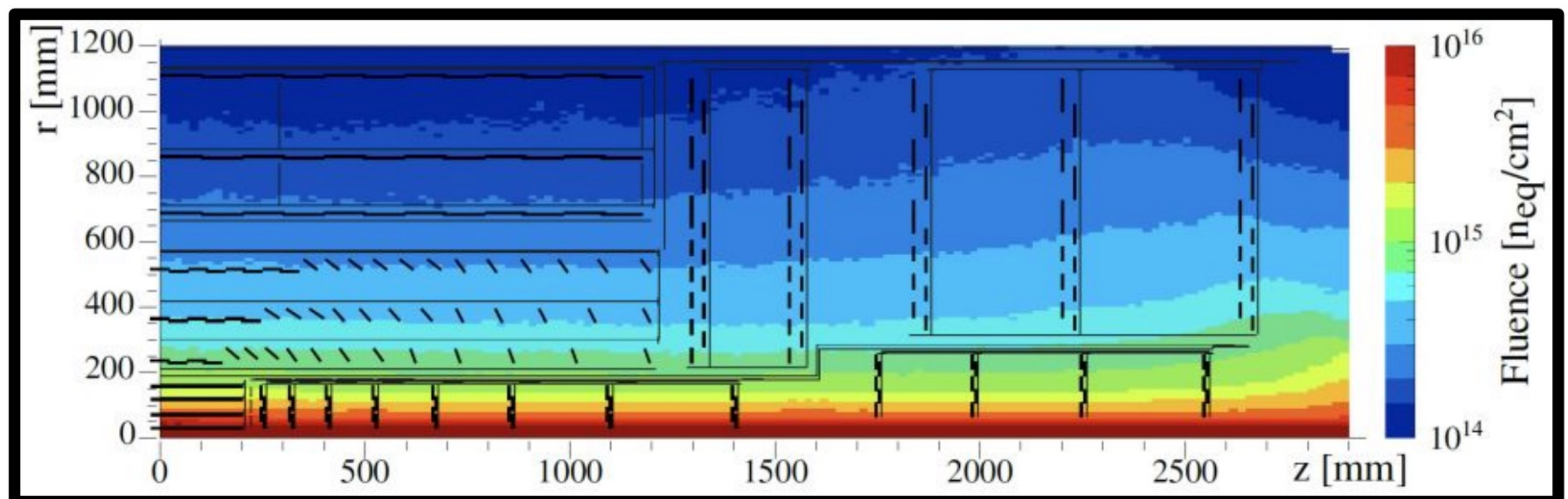
On behalf of the CMS Experiment

The Catholic University of America

Motivation



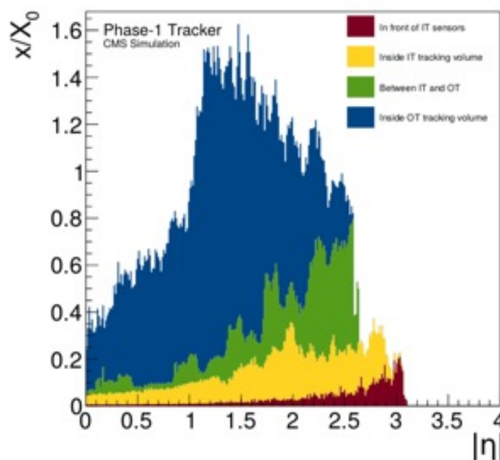
- Change in running conditions for LHC to HL-LHC
  - *Pileup increasing from 25 to ~200*
  - *Hit rate from 0.58 to 3.2 GHz/cm^2*
  - *Radiation from 300 to 3000 fb^{-1}*
- The above places the following requirements on the inner tracking detector
  - *Smaller pixels to reduce occupancy*
  - *Lower detection threshold to allow two track separation*
  - *Reduced material budget to improve tracking performance*

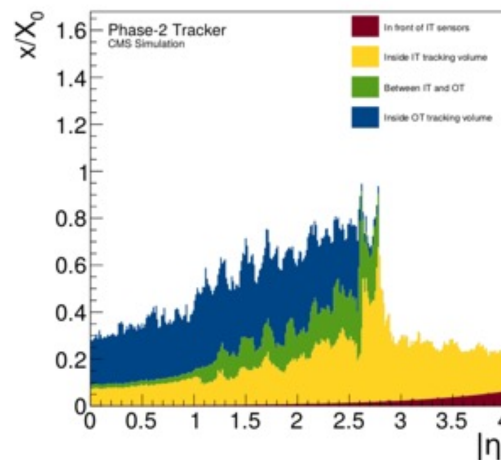


HL-LHC CMS Tracker

Outer Tracker (OT)

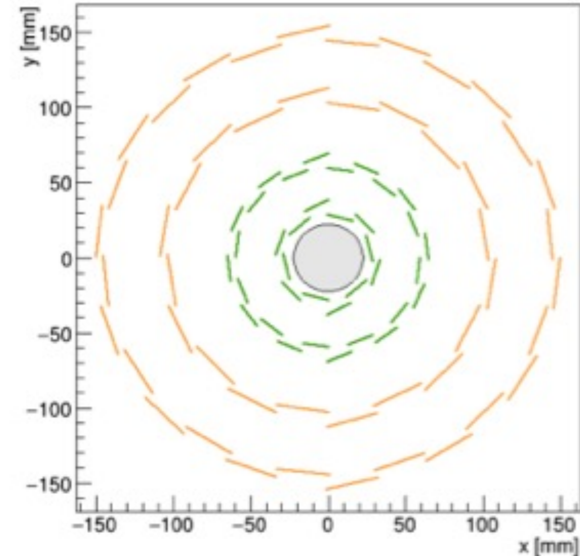
Inner Tracker (IT)



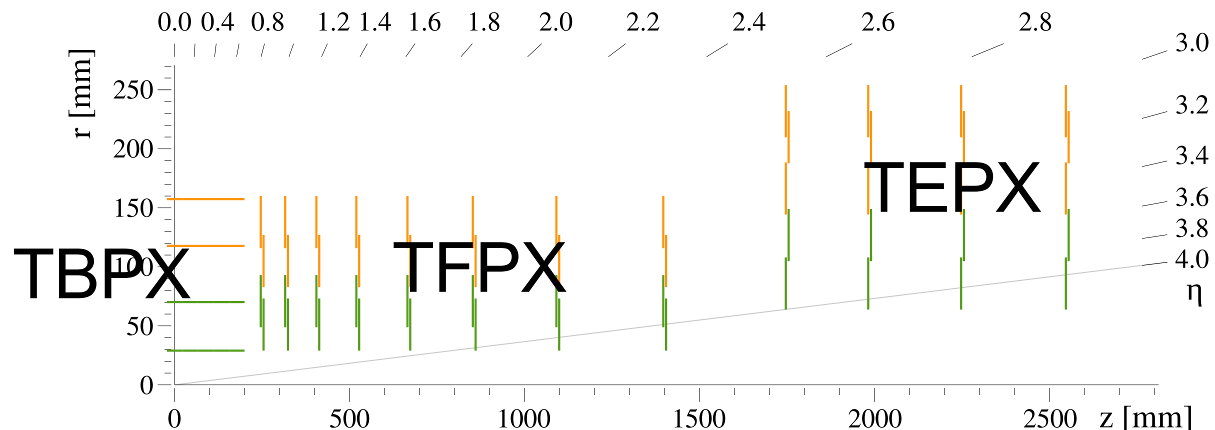


Talk on OT by Kevin Nash Next!

Detector Layout



- 4 large discs on each side (TEPX)
  - *Each disc made of 4 identical dees*
- 8 small discs on each side (TFPX)
- 4 barrel layers (TBPX)
  - *No crack at z=0*
  - *Two ladders per layer skewed in rφ for the insertion of CMS*
- Two types of pixel modules: 1x2 and 2x2 readout chips per module
- Extended coverage up to |η|= 4
- Innermost modules located at r = 2.75 cm form the beamline



the two types of modules described in the text.

HL-LHC US CMS

Inner Tracker: TFPX Scope

0.0 0.4 0.8 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2 3.4 3.6 3.8 4.0 η

TEPX

TBPX

TFPX – NSF scope

Beampipe

0 50 100 150 200 250

0 500 1000 1500 2000 2500 z [mm]

High Density Interconnect

HDI

Bumpbond

Sensor

ROC

Wirebond

ReadOutChip

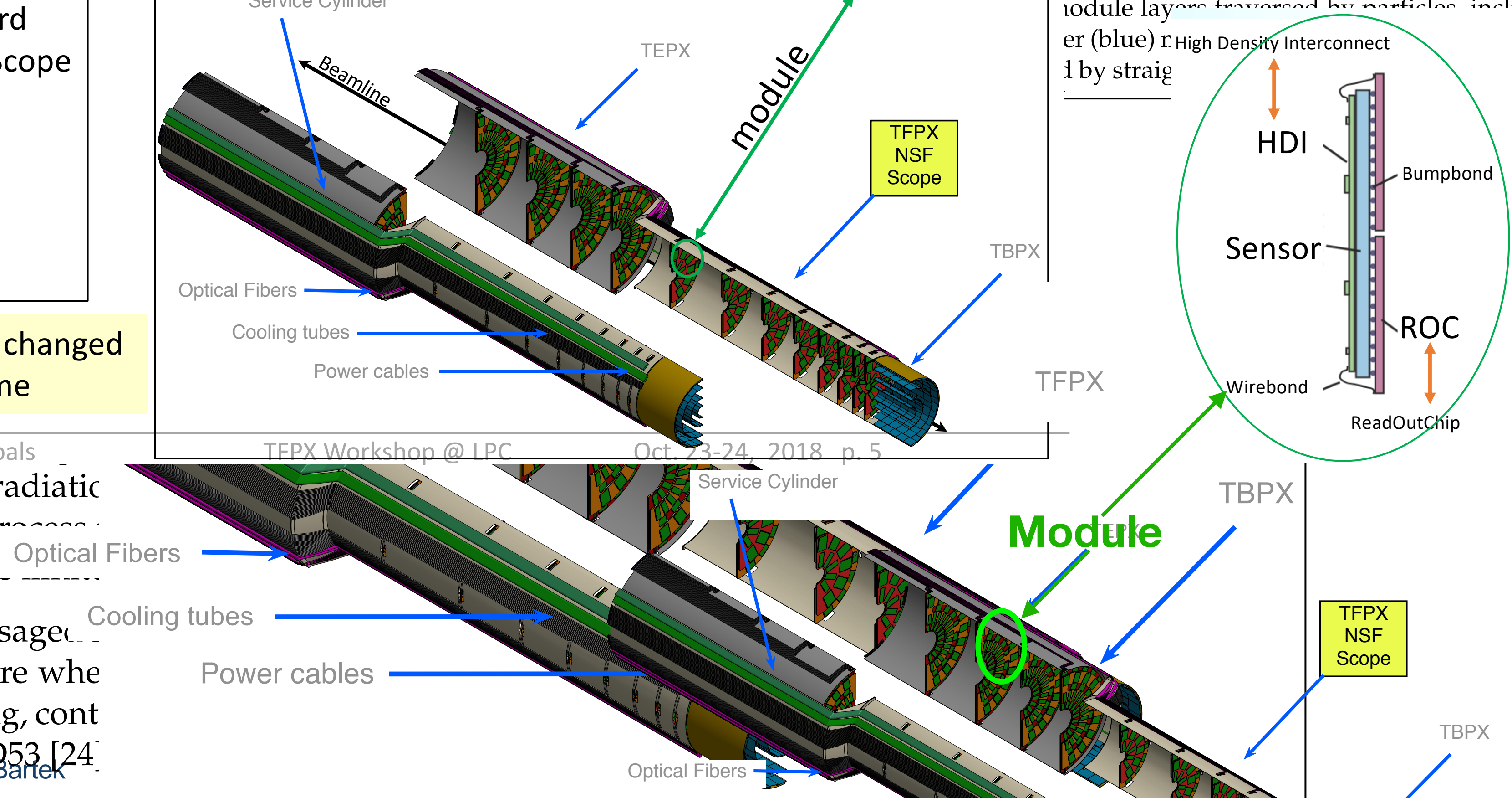
enance

shutdown 5

TFPX – primary forward tracking device: NSF Scope

- 1.3 < |η| < 4
- 2x8 disks
- 1728 modules
- 0.8 Gigapixels
- 1.9 m^2 silicon area

Configuration slightly changed since CDR, area ≃ same



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R. Bartek

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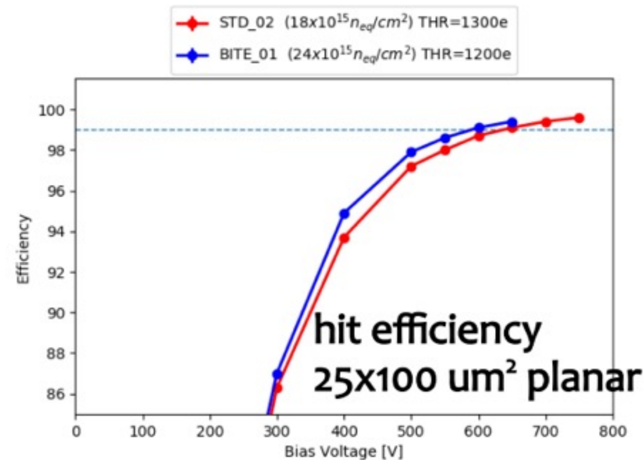
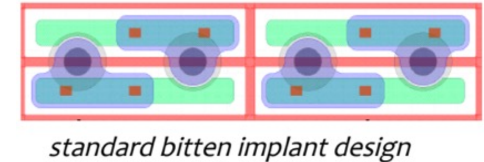
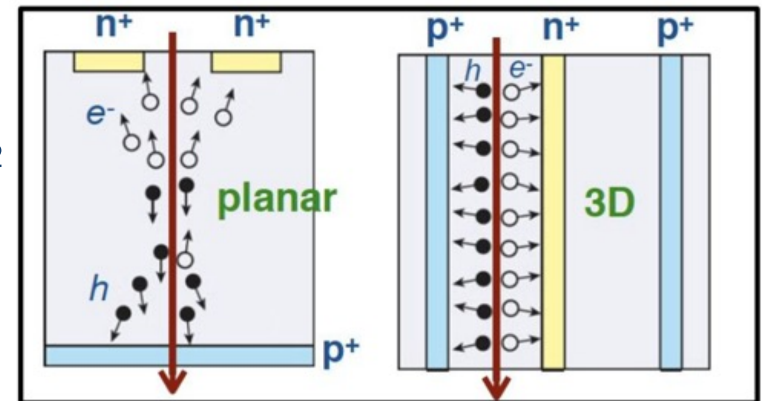
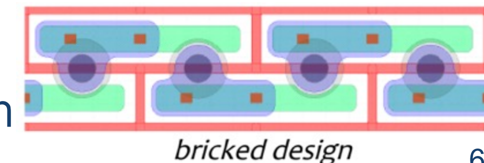
Inner Tracker Sensors



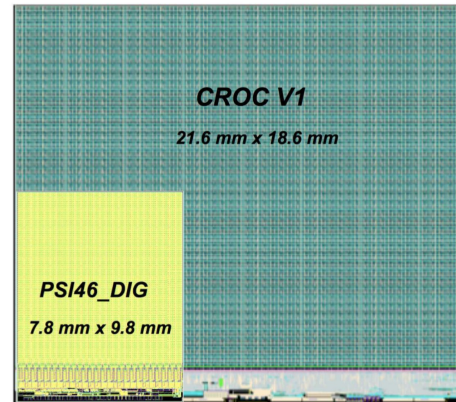

standard bitten implant design

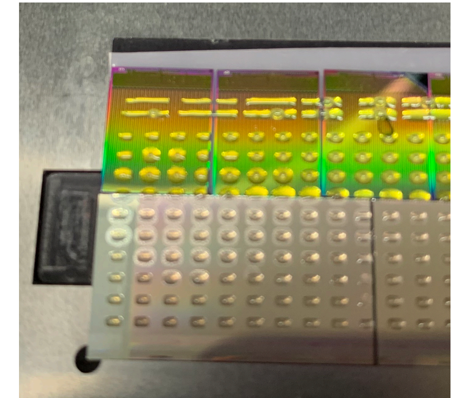
- Decision Q4 2021
  - *Intense R&D program*
  - *Baseline option:*
- n-in-p planar, 150 µm active thickness (~1.7kg silicon), 25x100 μm^2 cell size
- Bitten implant, no punch-through bias dot
- Hit efficiency > 99% after ~2.0e16 n_{eq}/cm^2
  - *Alternatives being studied:*
- 3D pixels for TBPX layer 1 and TFPX ring 1
  - *Better power consumption*
  - *Negligible degradation in hit resolution after 1.0e16 n_{eq}/cm^2*
- 50x50 μm^2 still considered for disks
- Planar sensors with bricked layout in the central η region




bricked design

C-ROC





- ASIC is based on CMOS 65nm technology within the CERN RD53 project
  - *Radiation tolerant up to 1 Grad (verified at high dose rate)*
  - *Robust against SEU effects*
  - *Bonding pad reticles fit both 50x50 and 25x100 μm^2 sensor options*
  - *Low power consumption < 1 W/cm^2 at max trigger rate (CMS Level1: 750 kHz)*
  - *Serial powering via on-chip shunt-LDO regulators (1 for analog, 1 for digital sections) to supply the needed 50 kW with a limited mass of the power cables*
- CMS version of RD53 ROC (C-ROC) wafers back at CERN
  - *Will be tested and green chips flip chipped*
  - *Full size ASIC: 432x336 channels*
  - *Analog FE linear architecture featuring an in-time threshold O(1000e)*
  - *4 bit digital readout with selectable 6-to-4-bit dual slope ToT mapping for charge compression (elongated clusters, heavy ionizing particles)*

TFPX – primary forward tracking device: NSF Scope

- 1.3 < |η| < 4
- 2x8 disks
- 1728 modules
- 0.8 Gigapixels
- 1.9 m² silicon area

Configuration slightly changed since CDR, area ≃ same

Service Cylinder

Beamline

TEPX

module

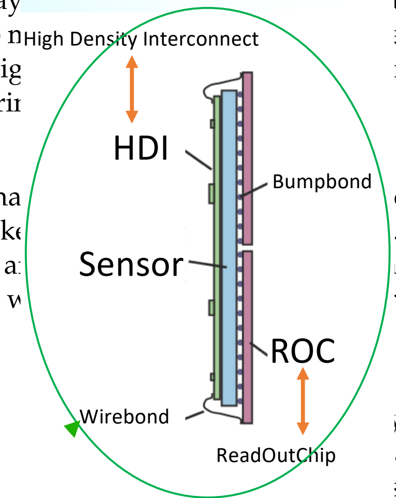
TFPX NSF Scope

TBPX

Optical Fibers

Cooling tubes

Power cables



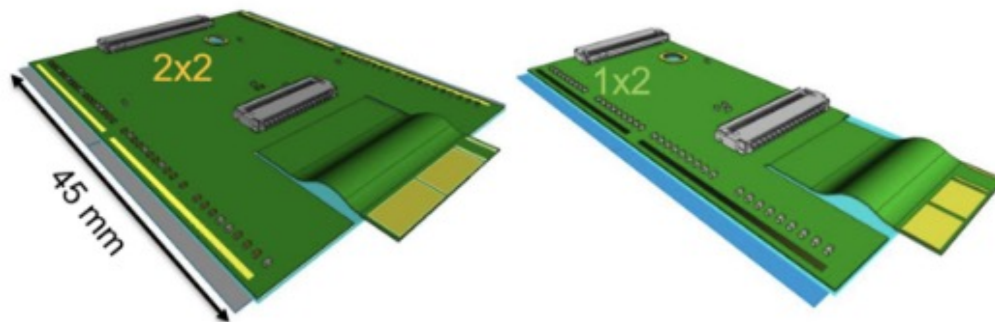
...odule layers traversed by particles, including ... er (blue) ... tra... d by straig... le scatterin... es the ma... se-2 tracke... opti... laye... e min... of |η| <

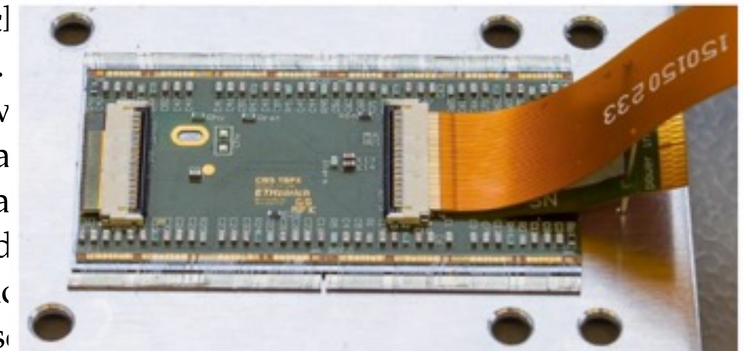
- Cable savers ... twisted pair cables fragile
- Geometry constraints:
  - TBPX: Both faces of barrel ... service routing on backside with supply ... return ... directly ... module to module
  - TFPX and TEPX: service routing on inactive surface

...ing intrinsically higher radiation re... the s... dis-e. Since the production process is more ex... not su... volumes, use of 3D sensors could be limited to the regions of ... the fluences.

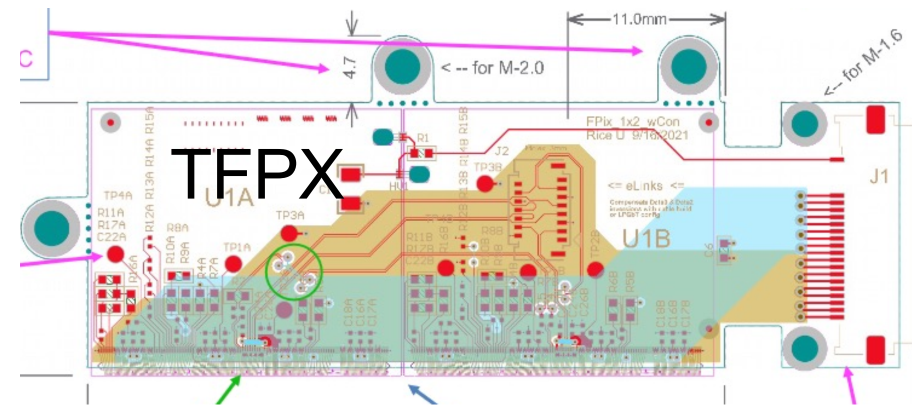
...he readout chip, the envisaged small cell size can be achiev... 65 nm ...nology and an architecture where a group of channels (referre... sh... ...al electronics for buffering, control, and data formatting. Such a pixel ... ...ing developed within RD53 [24], a joint ATLAS-CMS collaboration.

...baseline Inner Tracker layout is shown in Fig. 4.1. The number of laye... by parti... originating from the luminous region has been shown in Fig. 2.4, both for the ... tracker ...e and for the total tracker. The detector comprises a barrel part with four layers (referred to ...acker Barrel Pixel Detector, TBPX), eight small double-discs per side (referred to as Tracker ...ward Pixel Dete... ...Pixel Detector, ...rs". ..., neighbouring ... etw... is achieved. T... ...p a... ...oided by moun... ...ba... ...ics in z into sli... ...mod... ...nged in concen... ...vhic... to mount mod... ...disc... two halves, and these D-shaped structures are referred to as "dees". The TEPX will provide ...equired luminosity measurement capability, as detailed in Section 10.3, by an appropriate ...ementation of the readout architecture. In total, the pixel detector will have an active sur... of approximately 4.9 m². More details on the layout and on hermeticity are provided in

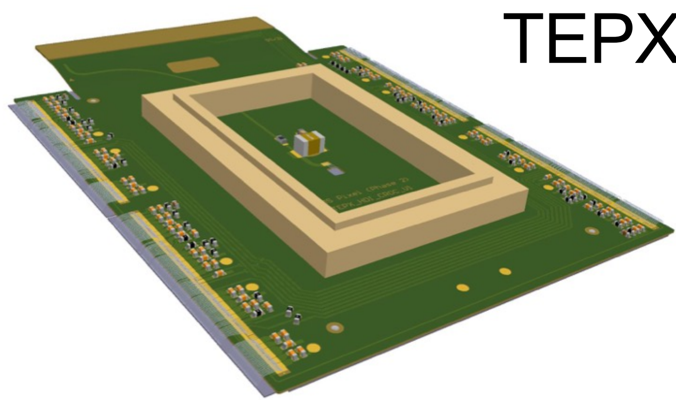


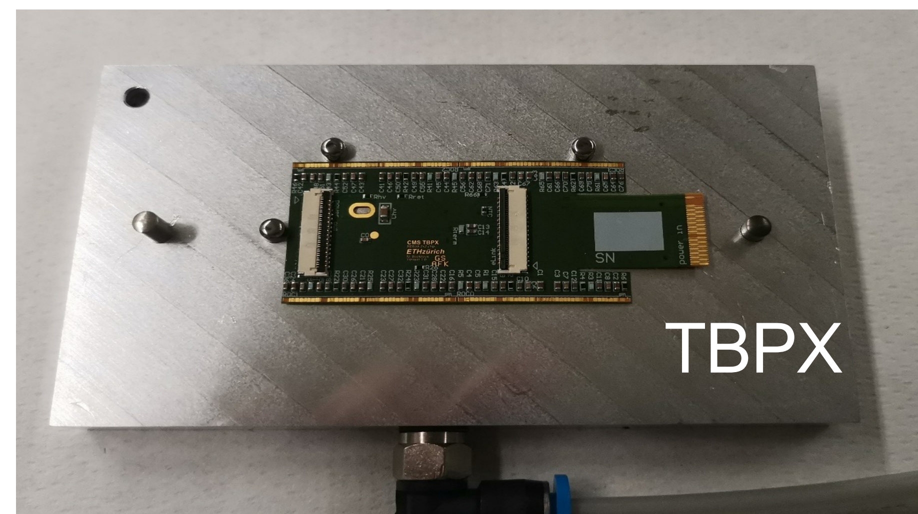


HDI



- Flexible PCB containing only passive components
  - *High precision resistors and decoupling capacitors*
- HDI contains return path for supply current
- Careful design for current paths to preserve low material budget
- HV capable of up to 1000 V





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TEPX

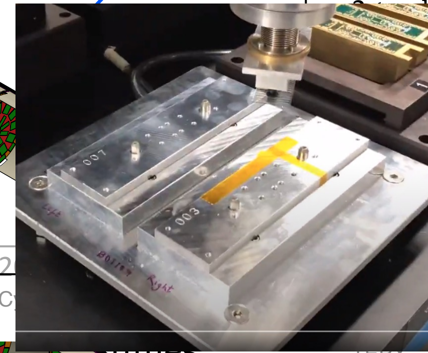
module

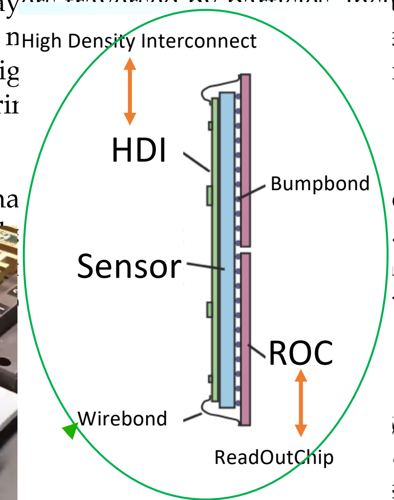
TFPX NSF Scope

Optical Fibers

Cooling tubes

Power cables





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- TFPX module ... otic
- Glue stamps and ste... ites
- After HDI glued to module, a... nect HDI and readout chip
- Paralyne-N coating for spark protection ... to ... voltage of 800V

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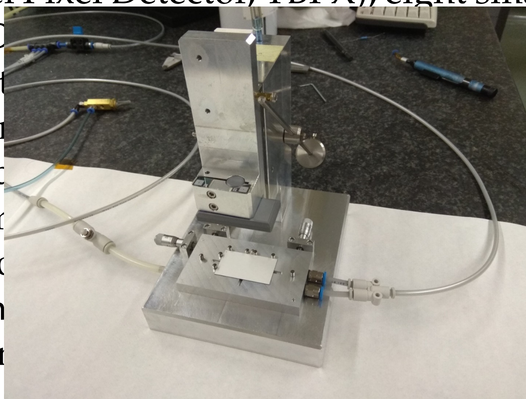

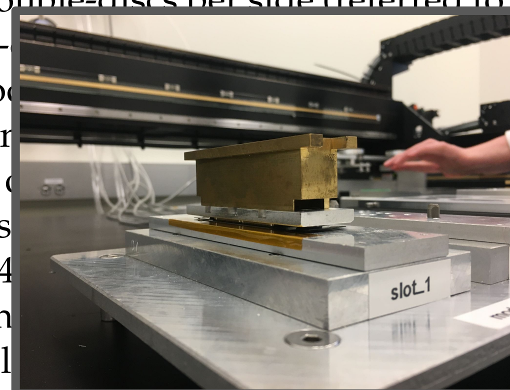

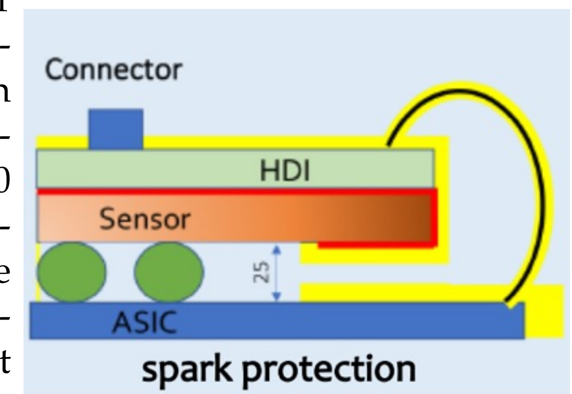

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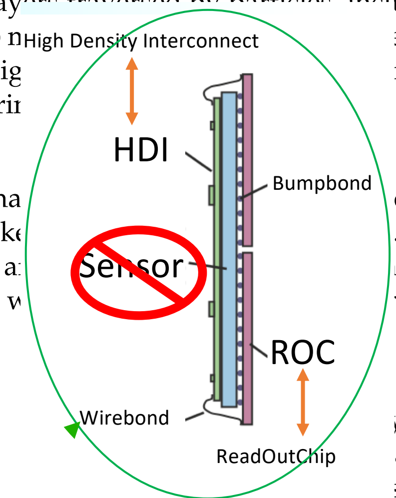

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vard Pixel Detector, TFPX) and four large double-discs per side (referred to as Tracker End-
Pixel Detector, TEPX). In the TBPX the pixel modules are arranged in "ladders". In each
, neighbouring ladders are mounted staggered in radius, so that r-φ overlap between lad-
is achieved. The modules on a ladder do not overlap in z. A projective gap at $\eta = 0$
oided by mounting an odd number of modules along z, and by splitting the barrel me-
ics in z into slightly asymmetric halfs (Section 4.4). In TFPX and TEPX the modules are
nged in concentric rings. Each double-disc is physically made of two discs, which facili-
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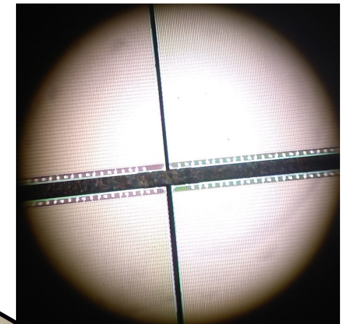
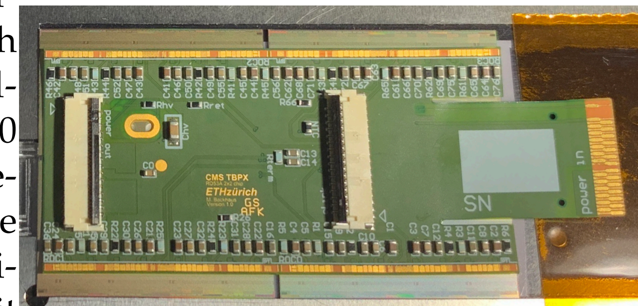
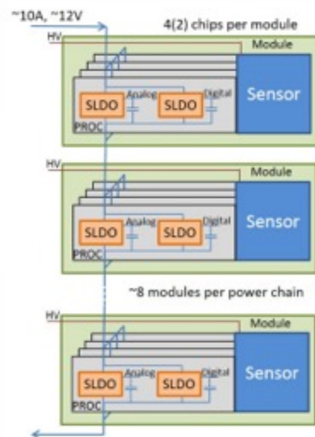
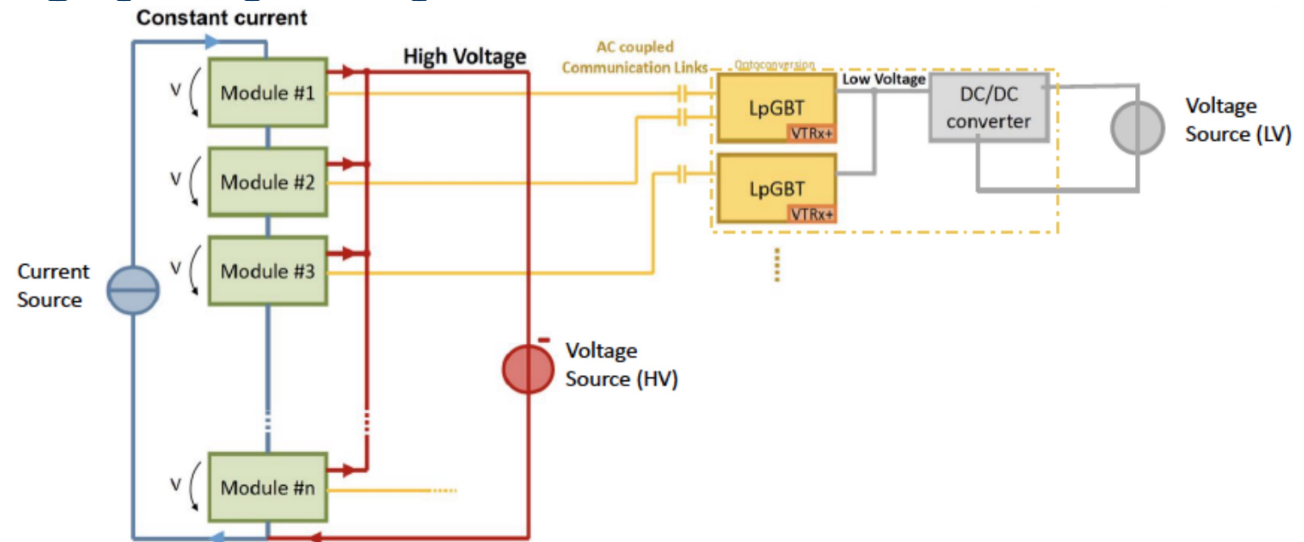
- Useful for t… deve… …nds, and establishing as… …ng bonding parameters
- Have made with RD53A chips
- Plan to make with CROC chips while other … be… chipped
- Challenge to leave some space between ROCs but have them positioned similar to bump bonded modules





Powering Scheme

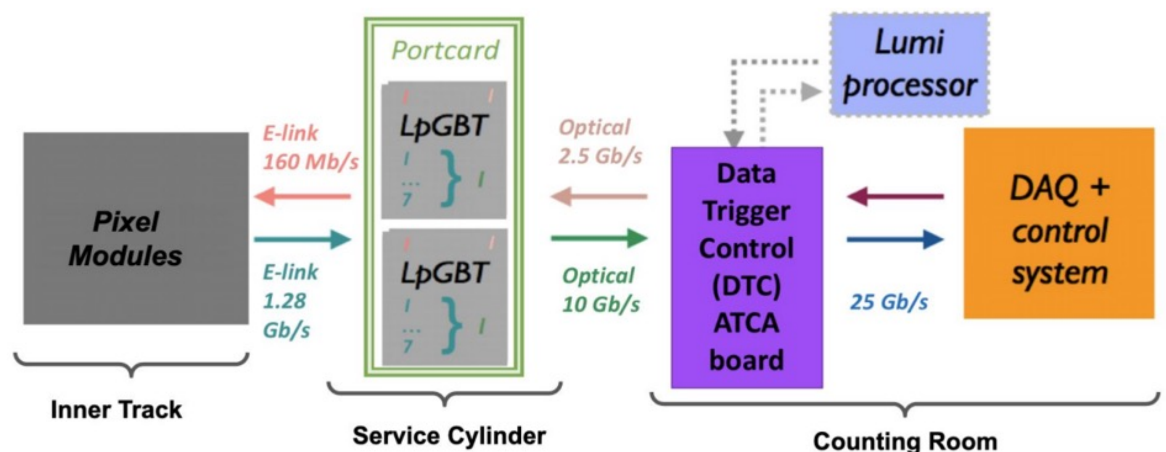




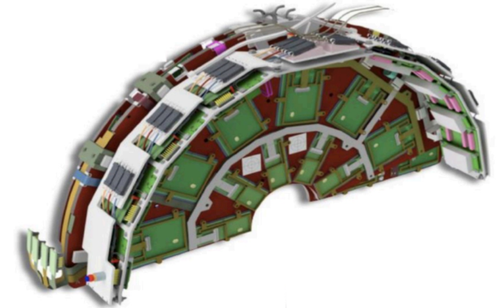
- Serial power
  - *Modules grouped in 500 serial power chains, up to 12 modules in a chain*
    - Modules powered in series, chips within each module powered in parallel
    - A shunt-LDO (SLDO) on each chip provides voltage regulation for each chip while maintaining a constant current
  - *Chips in a module in parallel (4A for 1x2 modules, 8A for 2x2 modules)*
  - *Sensor bias following the serial power chains with single return line*
  - *Single power supply module: current source (SP), HV for sensor (0-800V), LV for portcards and pre-heaters required by CO_2 cooling*
  - *Only copper cladded aluminum wires in the detector volume*

Readout Architecture

- Custom ASICs, LpGBT, VTRX+
- Up to 6 electrical up-links at 1.28 Gb/s per module to LpGBT
  - *Data formatting to reduce data rates by half*
- One electrical down-link at 160 Mb/s per module from LpGBT
  - *Clock, trigger, commands, configuration data to modules*
- 28 Data Trigger Control boards required for inner tracker
- Portcards optoelectronic service card
  - *2x LpGBTs and VTRx+ links, powered via cascaded DC-DC converters*

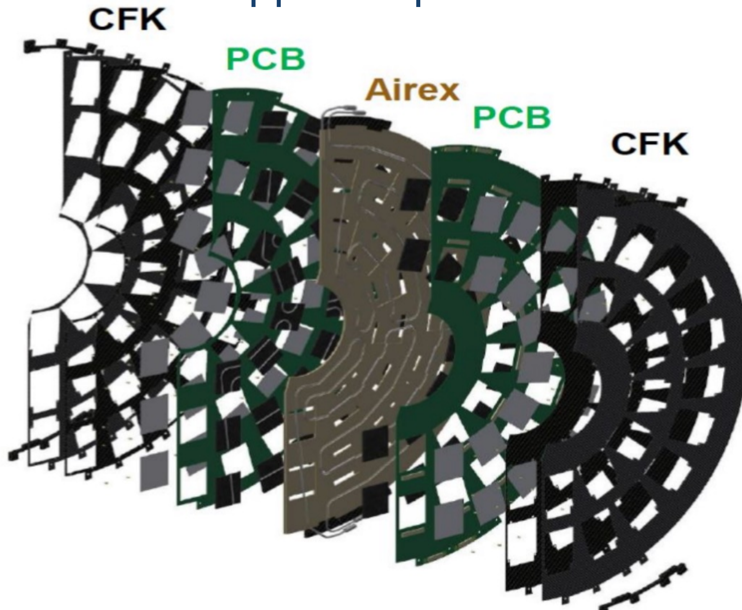


Mechanical Support



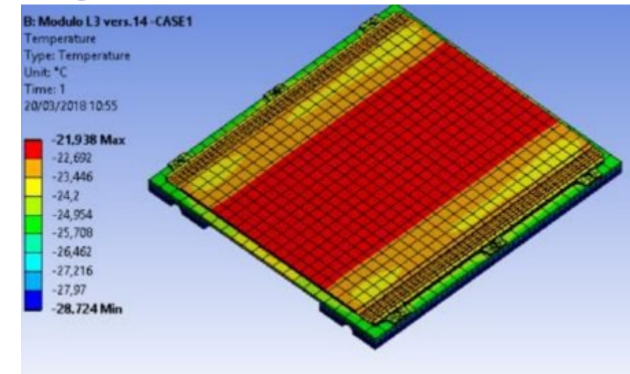
- Light Carbon Fiber structures with embedded cooling pipes
- Disks with flat geometry (unlike turbine in current detector)
- Improved fiber routing which reduces radiation induced attenuation
- Cooling based on evaporative CO_2 (T=-35°C) distributed in 1.8 mm outer diameter stainless steel pipes (168 cooling loops)

TEPX Support exploded view

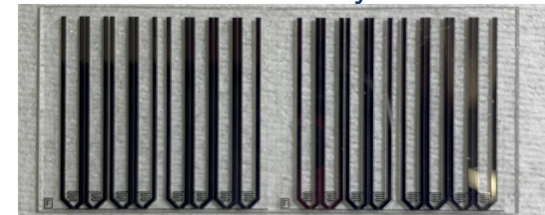


Dee composed of symmetric sandwich:

- Central layer CO_2 pipe and Airex foam
- Thermal Pyrolytic Graphite
- Electrical Isolation: Aluminum Nitride
- Dee-PCB with electrical services
- CFK panel and modules



Glass heaters to mimic module thermal needs to verify simulation



Summary

- It is extremely challenging to design an inner tracking detector that can fully exploit the high instantaneous and integrated luminosity expected from the HL-LHC
- Prototyping phase is still on-going
  - *Several RD53A modules made to test sensor options*
  - *Digital modules made and being tested*
  - *Sensor technology decision expected soon*
- Construction will not mark the end of R&D efforts for the inner tracker as part will be replaced halfway through HL-LHC run
- The CMS HL-LHC upgrade is ambitious, by necessity, but major progress has been made