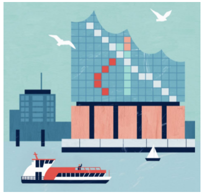
A. Shevelev on behalf of BRIL (CMS)

Upgrade of the CMS luminosity instrumentation and the Fast Beam Condition Monitor for HL-LHC

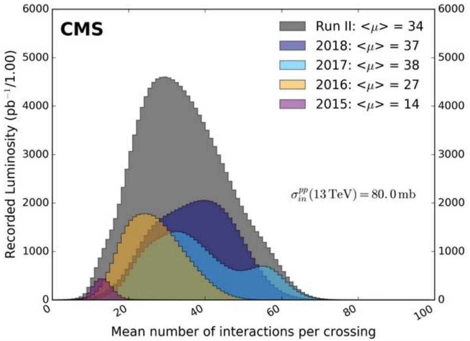


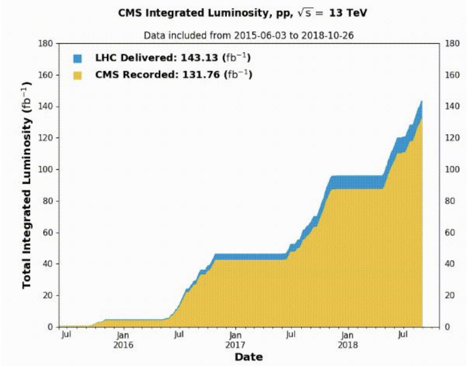
European Physical Society
Conference on High Energy Physics,
August 21st 2023

Beam Radiation, Instrumentation, and Luminosity (BRIL)

BRIL - Beam Radiation, Instrumentation, and Luminosity Project of CMS

- Responsible for various detector systems for beam instrumentation, control of background conditions, monitoring & simulation of radiation environment
  - Beam dump functionality in case of dangerous beam losses events
  - Provides technical triggers for CMS L1 Global Trigger (GT)
- Delivering precise luminosity measurements (together with Luminosity Physics Object Group)



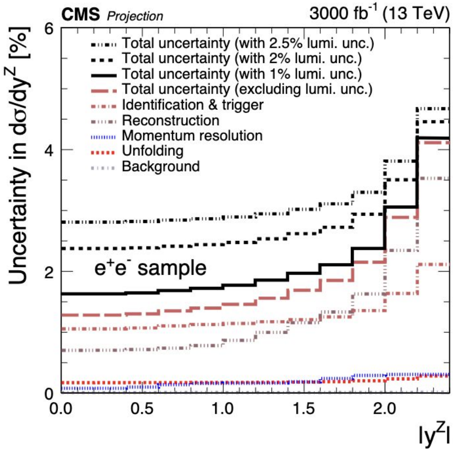


Main challenges for luminosity in Phase-II

- Increase in luminosity ~10x LHC's design value
- Pile-up: up to 200 interactions per one bunch-crossing

Luminosity precision goal for Phase-2 is ambitious: 2% online and < 1% offline

- Integrated luminosity has become one of the largest sources of experimental systematic uncertainty in many physics analyses



The relative systematic uncertainties from various sources in $|y^Z|$-differential Z boson cross section measurements in the dielectron final state. The black lines show the total uncertainty for different values of the luminosity uncertainty, and the colored lines show other contributions [CERN-LHCC-2021-008]

Multiple detectors with different systematics to achieve the luminosity precision goal and provide constant feedback to LHC

Fast Beam Condition Monitor (FBCM):

- Dedicated Luminometer independent from CMS DAQ and main services
- Si-pad hits, zero-counting

Forward Hadron Calorimeter (HF):

- Hit tower counting (occupancy) and E_T sum:
  - One of the primary luminometers in Phase-0/1

Muon system (DT + RPC):

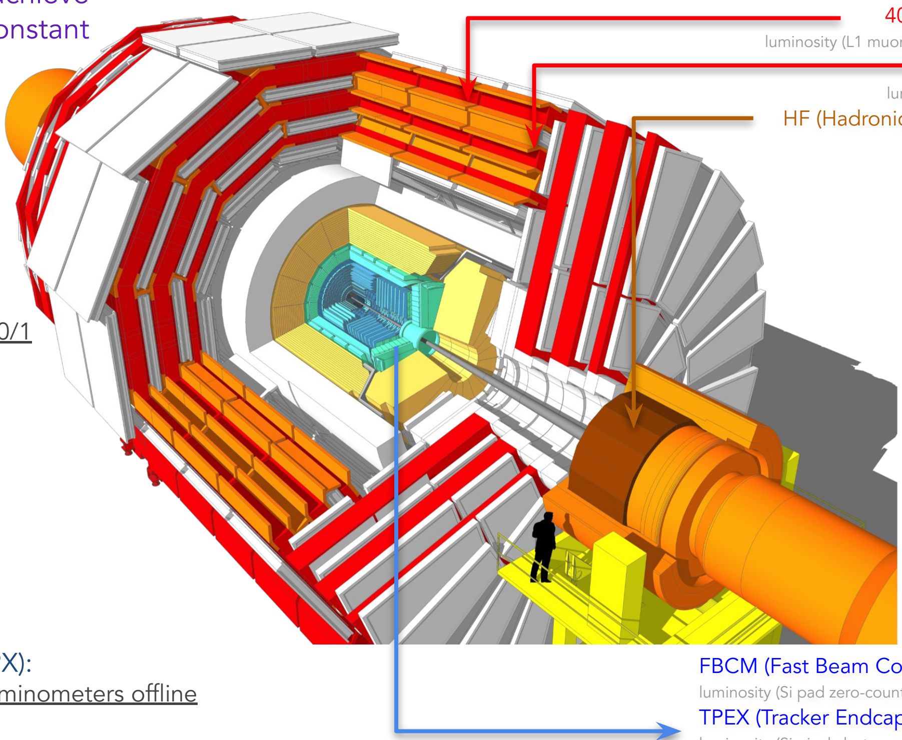
- Muon trigger primitives:
  - Phase-2 demonstrator installed for Run3

40 MHz L1 Trigger Scouting:

- Various Global Trigger objects
  - Muons, tracks, energy clusters, sums

Tracker luminosity:

- Outer tracker (OT) stubs and pixel clusters (TEPX):
  - Pixel cluster counting one of the primary luminometers offline in Phase-0/1 -> Online in Phase-2



BRIL Data Acquisition System and Histogramming Unit

Dedicated module will be implemented to back-end firmware of every system for real-time FPGA histogramming
- Allows to run independently of CMS Global Run
- The concept successfully tested during Phase-1 with HF Luminosity

Each clock cycle (from 40 to 320 MHz) count primitives delivered from front-end and increment corresponding bin
- e.g. number of muon stubs, hits/clusters, Σenergy deposition

Data aggregated for every BCID over multiple orbits and read by software via IPBus (or TCP):
- Typically every 1s and propagated to BRILDAQ, CMS DAQ and LHC

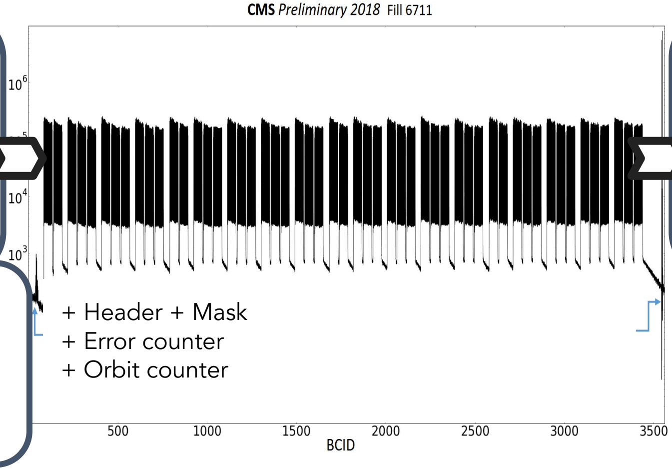
Detector per time bin per channel
- Count increment (e.g. #objects / Σenergy)
- Error flag(s) from FE, BE

Detector back end
(data source)

- Data formatting
- Aggregation to lumi channels
- Histogramming

Configuration parameters
- Integration time (#orbits)
- Counter size (#bits)
- Time bins (#bins / 25 ns)

TCDS Information
- Fill/Run/LS/Lumi word



+ Header + Mask
+ Error counter
+ Orbit counter

- Data aggregation via IPBus
- SoC processing
- Distribution to subscribers (BRILDAQ, CMS DAQ, LHC)

Online Tracker Luminosity using TEPX and OT

Real-time Pixel Cluster Counting (PCC) with TEPX

- Additional 75 kHz of luminosity triggers (10% on top of the nominal L1A rate of 750 kHz)
- TEPX (Disk 4 Ring 1 - D4R1) is beyond η = 4 and will not be used for tracking
  - BRIL operated (even outside of stable beams)
  - Lumi and background at the maximum possible trigger rate: 825 kHz at PU200, 2-4 MHz at low PU

Luminosity Triggers for TEPX & D4R1 will be provided by a dedicated BRIL Trigger Board (BTB)

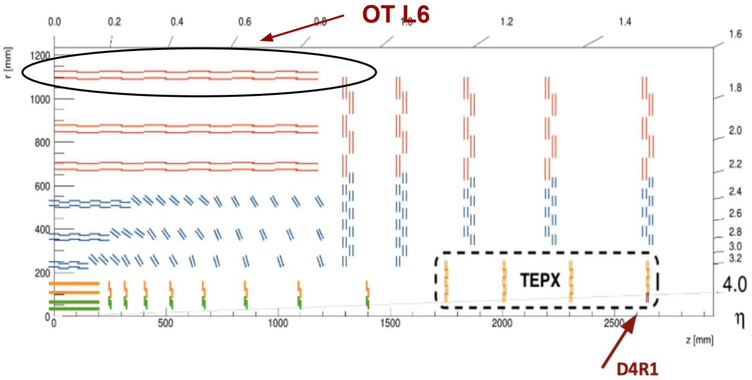
- Also receives the Beam Pickup Timing Experiment (BPTX) signals and forwards them to the Global Trigger (GT)
- BRIL is exploring options for dynamic trigger rate allocation between GT & BTB

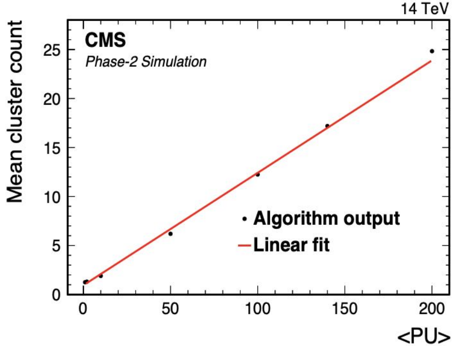
Outer Tracker Layer 6 - Best statistical power

- Tracker stubs counted at 40 MHz but available only during Stable Beams

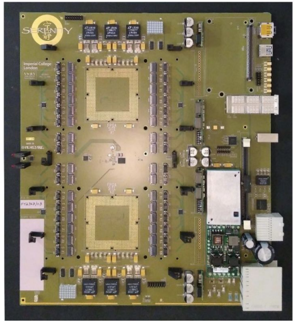
Cosmic test-stand built at CERN (Tracker/BRIL)

- histogramming module was successfully tested
- migration to Apollo/Serenity boards is planned





Simulated TEPX D4R1 mean cluster count as a function of pile-up



Serenity Prototype for BTB

Fast Beam Condition Monitor : Concept

There is a strong need for an independent, simple BRIL operated detector, capable to work in any conditions at full collision rate of 40 MHz

- The detector should be ready to provide luminosity and beam-induced background (BIB) measurements at the first day of HL-LHC commissioning

Fast Beam Condition Monitor (FBCM) is a design evolution of the Run-3 BCM1F concept

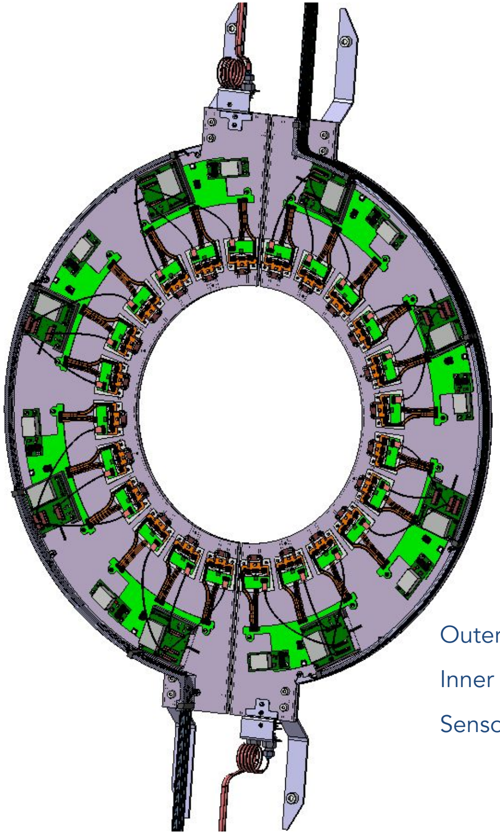
- BCM1F: stand-alone luminometer using cooled Si-pad sensors
- Fast, custom, asynchronous FE ASIC with peaking time of 6-9 ns (adjustable)
- Simple: semi-digital output, signal processing at the back end

Measuring BIB & luminosity by applying the ‘zero-counting’ algorithm with hits on Si-pad detectors

- Significantly increasing the channel count in Phase-2 (48 → 288 channels)

Modernising the electronics & system architecture - using standard HL-LHC electronics components (lpGBT, VTRX+ & DC-DC converters) in a modular design

- Widely used across CMS and qualified to the radiation levels at the FBCM location



Outer Radius R = 255 mm

Inner Radius r = 120 mm

Sensors radius r = 145 mm

Fast Beam Condition Monitor : Design

Moving from a tightly integrated detector system to a highly modular system

- To avoid 'single-point-of-failure' scenarios for large detector sub-assemblies
- To facilitate design, production and integration
- To ease the replacement of failing components

FBCM uses a fully symmetric design

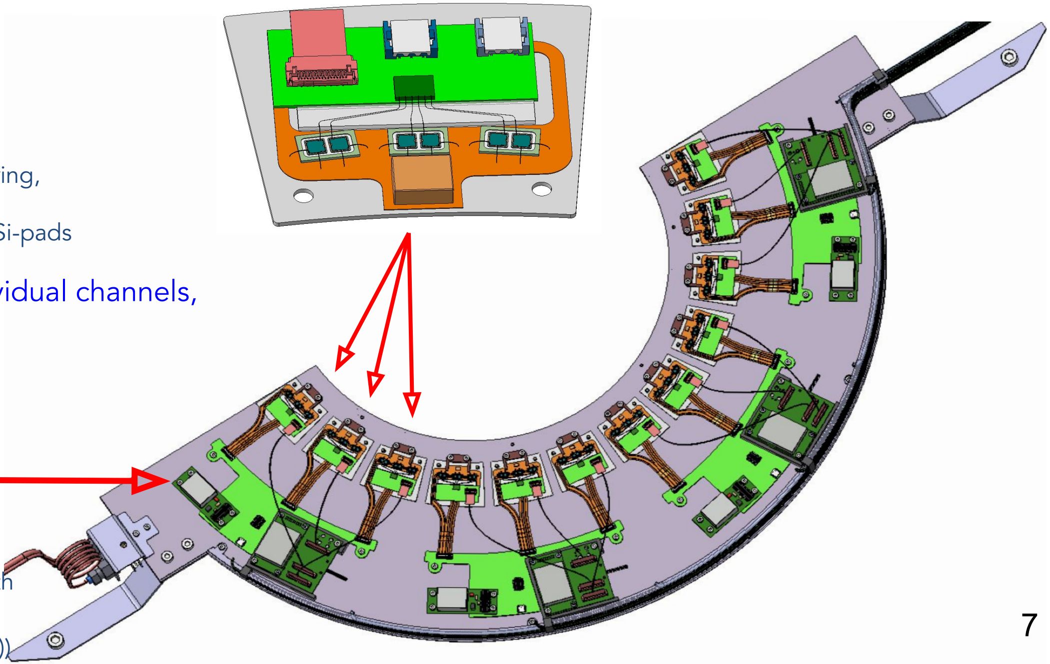
- Identical mechanical disks for all four quadrants

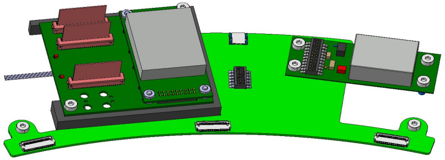
Identical service quadrants within a single disk

- A large service board providing HV/LV, slow-control, monitoring, calibration strobe & optical read-out for
- 3 identical front-end modules with a single FBCM ASIC & 6 Si-pads

FBCM performance is highly tolerant against loss of individual channels, yet maintain maximum practical granularity in services

3 front-end modules per service quadrant

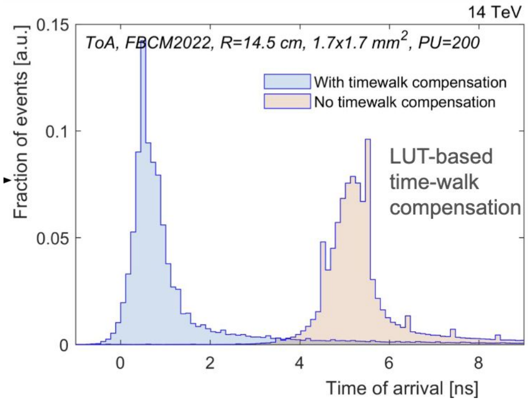




4 identical service boards with
1 DC-DC bPOL12V
1 IT portcard (DC-DC mezzanine + 3 x (e-link, lpGBT, VTRX+))

A heart of the system is fast, custom-developed ASIC

- Joint developments by BRIL and CERN-ESE, prototype expected on schedule in a few weeks



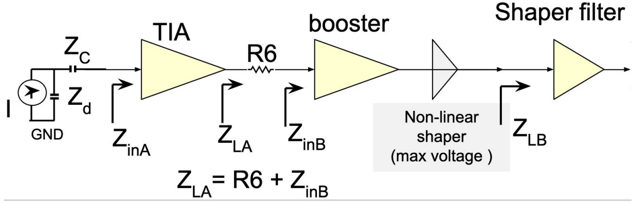
FE ASIC with semi-digital output starting at ToA and lasting ToT, sampled upstream by lpGBT

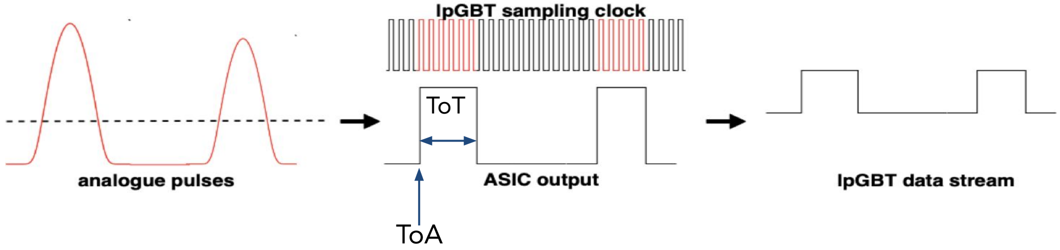
- Low-noise below 900 e-
- Double hit resolution after discrimination: 25 ns
- Fast return to baseline after hit with multiple MIPs (150 fC)
- 6 channels, trigger-less readout, signal processing in ATCA back-end (Apollo board)

Large effort put to model the full read-out chain in CMSSW

- Expected timing resolution after time-walk compensation ~1 ns (FWHM)

Radiation hard 65 nm analogue front-end ASIC designed for expected dose and fluence in FBCM location (200 Mrad and 2.5×10^{15}n/cm2)





Fast Beam Condition Monitor : Sensors

At FBCM sensor location expected 1 MeV n eq fluence is about 2.5×10^{15} for 3000 fb^{-1} (OT: 1.5×10^{15}; IT: 1×10^{16})

BRIL developed the test system for FBCM ASIC

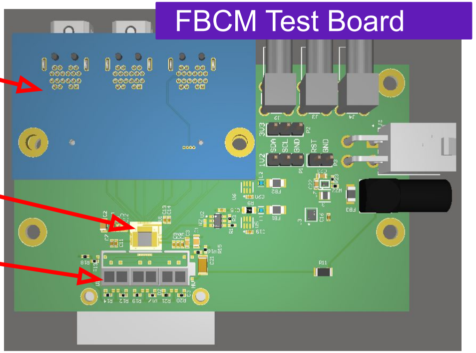
- Highly modular design, ready for tests, waiting for the ASICs

Two types of sensors are available for tests:

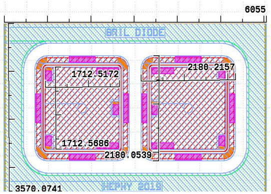
- 290 um (same as used in Run 3 BCM1F system, produced on OT PS-s wafers)
  - Better S/N both before and after irradiation but high leakage current → high shot noise
  - Qualified for 1.5×10^{15} 1 MeV n eq fluence planning for replacement after about 1500 fb^{-1}
- 150 um (produced on IT wafers)
  - More rad-hard but lower signals; lower leakage current & shot noise
  - Common GND ring to limit sensitive volume

Final choice after test beam with ASIC and both types of irradiated sensors

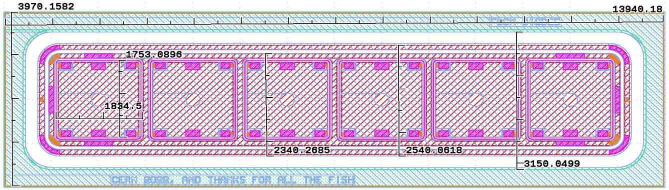
FBCM Test Board



AlN ceramic base



3* 2-pad, 290 um thick



6-pad, 150 um thick

Summary

CMS will rely on multiple systems, both CMS Front-End (Inner and Outer Tracker, Hadron Forward Calorimeter, Muon and 40 MHz Scouting systems) and stand-alone detector FBCM to achieve 2% uncertainty online and < 1% offline

- All subsystems will use similar histogramming units to accumulate bunch-by-bunch statistics at the highest possible rate (up to 320 MHz) to provide luminosity and beam induced background measurements
- Inner tracker (TEPX and TEPX Disk 4 Ring 1) will require special unbiased luminosity triggers provided by BRIL Trigger Board

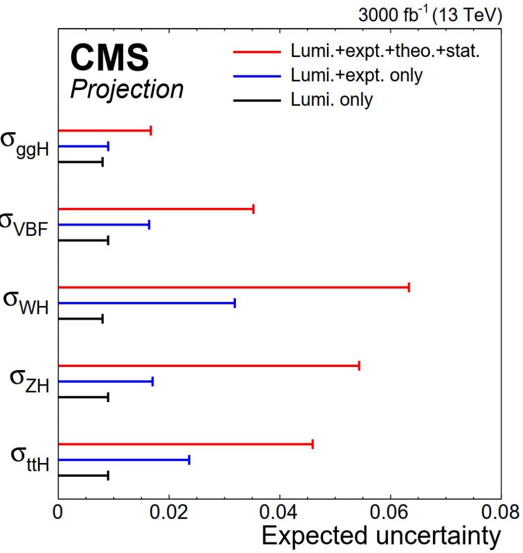
Dedicated luminometer Fast Beam Condition Monitor (FBCM) is under development. Ongoing prototyping.

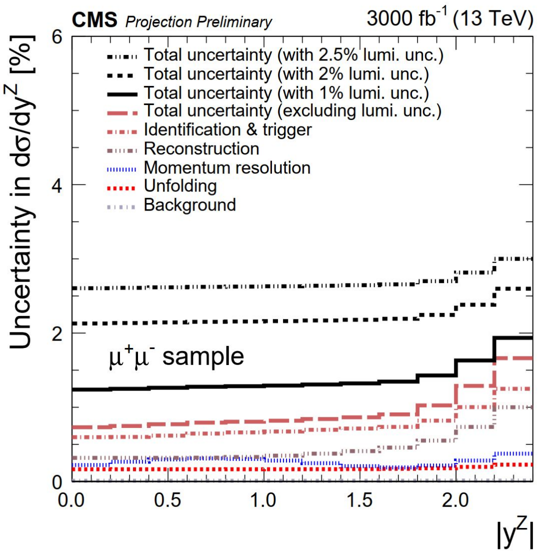
- FBCM is highly modular systems designed for robustness and maintainability
- Custom ASIC with fast peaking time and double-hit resolution of 25 ns
- ASIC and sensor irradiation campaign is scheduled. Final decision on the choice of the sensor technology will be made based on the outcomes

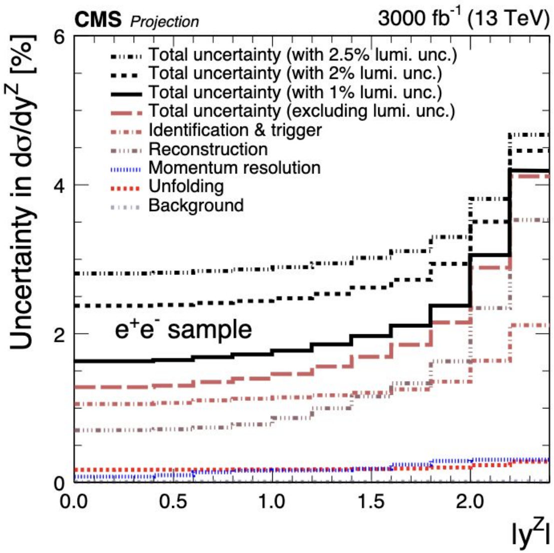
Luminometer Capabilities Summary for Phase-II

	Available outside stable beams	Independent of TCDS	Independent of foreseeable central DAQ downtimes	Offline luminosity available at LS frequency (bunch-by-bunch)	Statistical uncertainty in physics per LS (bunch-by-bunch)	Online luminosity available at ~1s frequency (bunch-by-bunch)	Statistical uncertainty in vdM scans for σvis (bunch-by-bunch)	Stability and linearity tracked with emittance scans (bunch-by-bunch)
FBCM hits on pads	✓	✓	✓	✓	*0.037%*	✓	*0.18%*	✓
D4R1 clusters (+coincidences)	✓	✓	✓	✓	*0.021%*	✓	*0.07%*	✓
HFET [sum ET] (+HFOC [towers hit])	✓	*if configured*	*if configured*	✓	*0.017%*	✓	*0.23%*	✓
TEPX clusters (+coincidences)	*if qualified beam optics*	✗	*if configured*	✓	*0.020%*	✓	*0.03%*	✓
OT L6 track stubs	✗	✗	*if configured*	✓	*0.006%*	✓	*0.03%*	✓
MB trigger primitives via back end	✓	✗	✗	✓	*0.25%*	✓	1.2%	✓
40 MHz scouting BMTF muon	✓	✗	✗	✓	*0.96%*	✓	4.7%	✓
REMUS ambient dose equivalent rate	✓	✓	✓	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*

Physics Requirements and Strategy







The relative systematic uncertainties from various sources in $|y^Z|$-differential Z boson cross section measurements in the dielectron final state. The black lines show the total uncertainty for different values of the luminosity uncertainty, and the colored lines show other contributions [CERN-LHCC-2021-008]

BRIL Data Acquisition System and Histogramming Unit

Two possible instances: Synchronous and Asynchronous

Both: Measure "primitives" send from Front-end independently from L1 and CMS DAQ and increase counts in particular bin corresponding to BX:

- Number of muon stubs, ΣEnergy deposition, Hits/clusters, Global Trigger events

Synchronous: data received and incremented each clock cycle (from 40 to 320 MHz)

Asynchronous: data received with fixed latency and recursively added to histogram (external information to match with clocks, double memory buffer)

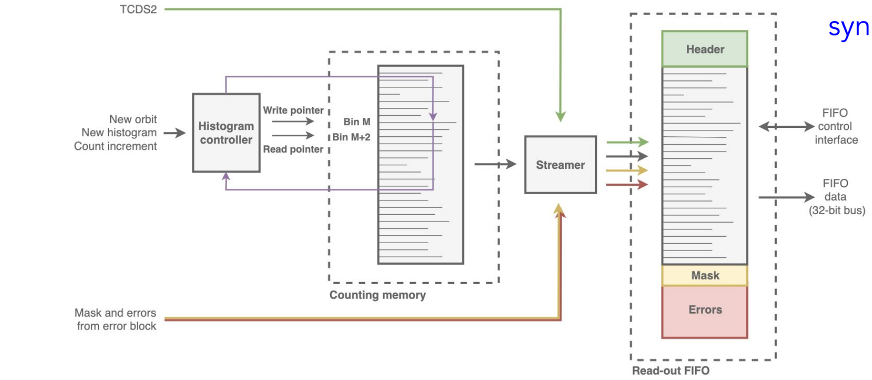
Sub bunch-crossing resolution for precise beam-induced background measurements

Data aggregated for each read-out channel over multiple orbits and resulted histogram is read by software via IPBus (or TCP/IP):

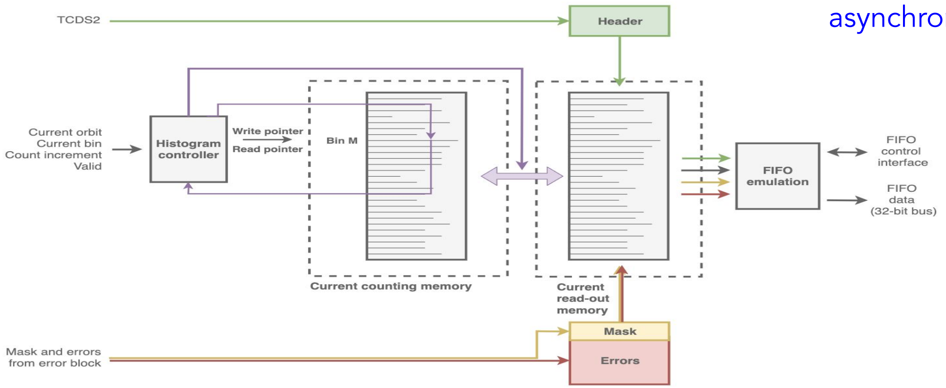
- Typically every 1.3 s (could be even 1 orbit)
- In Phase-2 will use back-end with SoC
- After software processing propagated to BRILDAQ, CMS DAQ and LHC

Implementation of the histogramming core

synchronous



asynchronous



BRIL Data Acquisition System and Histogramming Unit

One of the most essential ways to record luminosity data is histogramming

- Equal bunch spacing of 25 ns in LHC
- Data could be recorded from every bunch-crossing (BX) at maximal available rate:
  - for luminosity no need in single event granularity

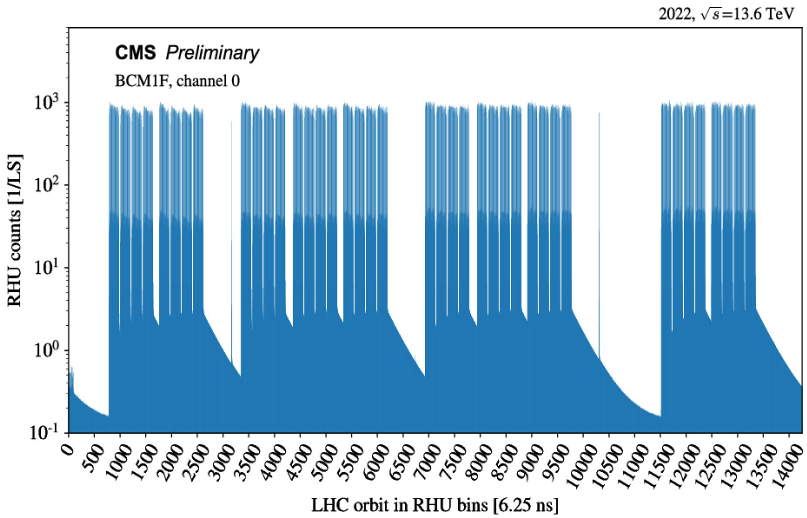
Keeping information on the rates in non-colliding BX may help to improve detector performance

- Evaluate background, account for out-of-time hits or luminosity dependent material activation (“afterglow”)

BRIL aimed to achieve maximal commonality in luminosity measurement approach for all subsystems (CMS or BRIL dedicated)

CMS propose to integrate “Generic histogramming module” into firmware of every system used for luminosity measurement

- Typically into back-end cards or dedicated luminosity processing “blades” (ATCA form-factor)
- With design which allows to operate outside of CMS Global Run (only requirement is configured TCDS)
  - The concept is successfully proven with HF Luminosity during Phase-1



Example histogram of measured BCM1F raw counts normalized to LS (~23 s) and integrated over 6h. The “afterglow” tails following every bunch train are clearly visible. Detector has timing resolution of 4 bins each bunch-crossing

BRIL Trigger Board (BTB)

BRIL Trigger Board

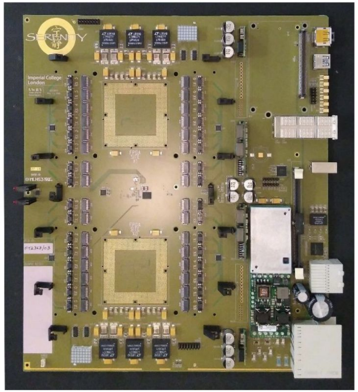
- Essential ingredient for the real-time Pixel Cluster Counting luminometry, will be based on Serenity board
- Generate and send luminosity triggers to TEPX - including BRIL operated Disk 4 Ring 1 (D4R1) - through central TCDS
- Receive the Beam Pickup Timing Experiment (BPTX) signals and forward them to the Global Trigger (GT)

Allow D4R1 and FBCM to operate outside of stable beams (BIB signatures are a lot cleaner when beams are not colliding)

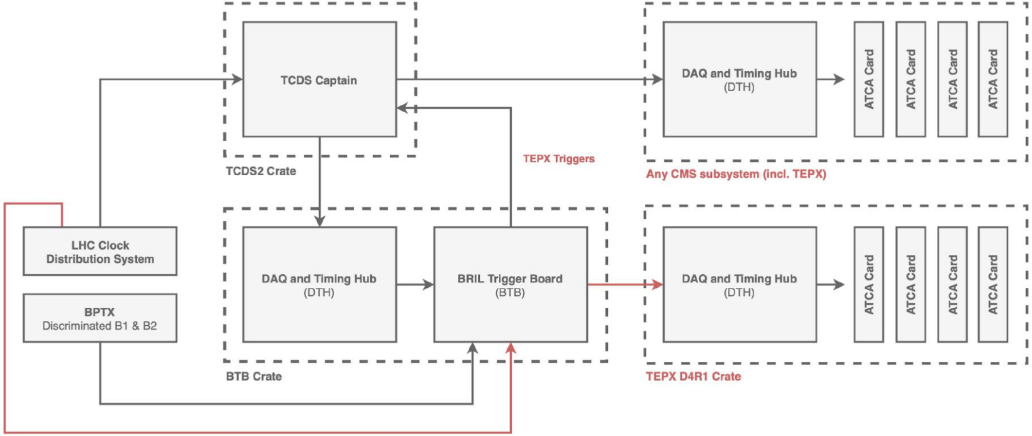
- Outside of STABLE BEAMS, CMS is on a local, fixed-frequency clock that is not phase locked to the LHC bunch clock
- Acting as TCDS Captain for these systems and providing a 'LHC-clock-based' local TCDS2 stream that maintains synchronisation with central commands

BRIL is exploring options for dynamic trigger rate allocation between GT & BTB

- With the purpose of increasing luminosity trigger rate at the expense of L1A rate when beneficial for the experiment, e.g. during emittance scans



Serenity Prototype



Other CMS Front End Luminometers

Hadron Forward Calorimeter

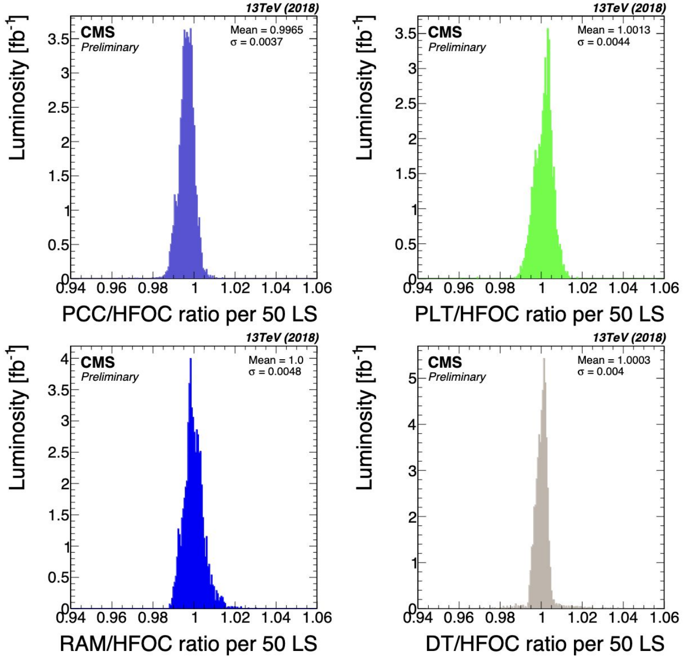
- Provides one of the most stable and reliable luminosity measurements to CMS using two methods: hit tower counting (occupancy) and E_T sum
  - Main concern: loss of performance due to aging and linearity at high pile up (PU)
  - HCAL upgrades the BE to ATCA to match the rest of CMS using the Barrel Calorimeter Processor (BCP):
    - 1 BCP board per HF side

Synchronous histogramming of trigger primitives (DT stubs)

- In Phase-2 hits from DT and RPC detectors will be combined to reconstruct muon track segments
  - Simulations and Run2 data (limit time granularity of 23s/no per bcid data) demonstrate great linearity and stability
- Demonstrator system with histogramming unit installed for Run3

Asynchronous histogramming of trigger objects (40 MHz Scouting)

- Opens opportunity for real-time counting various objects (including tracks, muons, calorimetry)
  - Triggers received in ~6 cycles of an independent 250 MHz clock
- Tests on-going in Trigger lab



Run2 experience: Ratio histograms for different pairs of luminometers: (top left) PCC/HFOC, (top right) PLT/HFOC, (bottom left) RAMSES/HFOC, (bottom right) DT/HFOC [CMS PAS LUM-18-002]

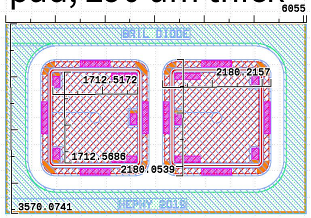
Fast Beam Condition Monitor : Sensors

At FBCM sensor location expected 1 MeV n eq fluence is about 2.5×10^{15} for 3000 fb^{-1} (OT: 1.5×10^{15}; IT: 1×10^{16}), planning for replacement after about 1500 fb^{-1}

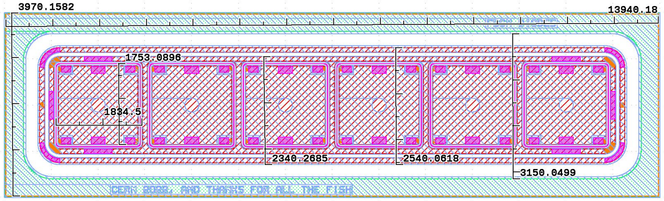
Two types of sensors are available for tests:

- 290 um (same as used in Run 3 BCM1F system, produced on OT PS-s wafers)
  - Prerad: S/N ~35, Noise rate ~ 6.1×10^{-109} Hz
  - After 1×10^{15} S/N=10.7, Noise rate ~ 3×10^{-5} Hz
  - Not qualified for 2.5×10^{15}, thermal runaway can be suppressed by excellent cooling contact (not a requirement, to be tested)
- 150 um (produced on IT wafers, signal to noise ratio after irradiation will be important to validate these sensors for use in final system)
  - Prerad: S/N=17, Noise rate ~ 2×10^{-20} Hz
  - After 2.5×10^{15} S/N~8, Noise rate ~ 50 Hz
- Final sensor choice after test beam with both types of irradiated sensors.

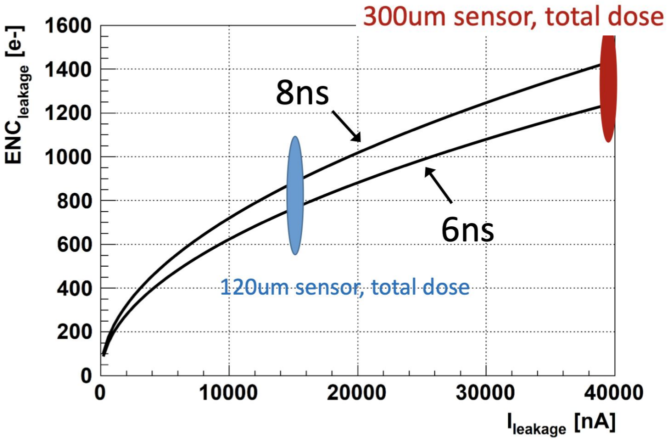
2-pad, 290 um thick



6-pad, 150 um thick



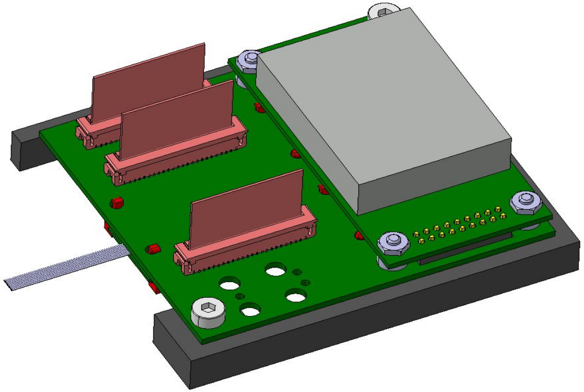
Shot noise from detector leakage assuming CR-RC^3 filter with 6 ns and 8 ns peaking time:

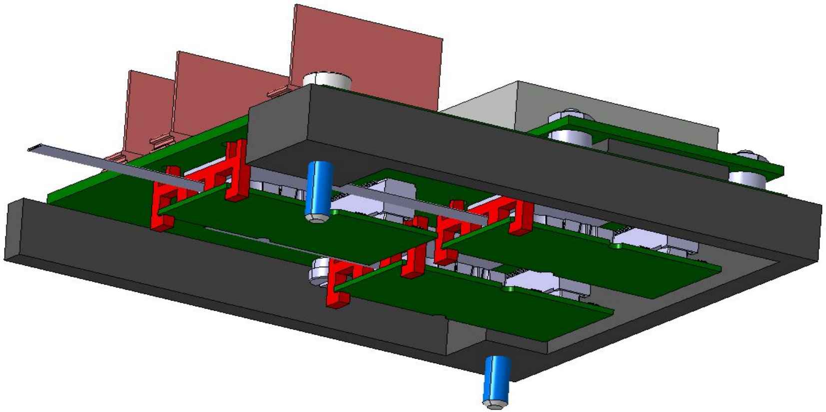


Taking into account degraded signal, the shot noise of the sensor leakage will define the S/N at the end of time life.

Portcard Frame

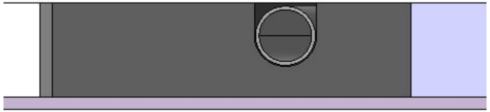
- Frame in Pocofam for thermal conductivity
- Studies of the pocofoam are ongoing: impregnation with glue to make it more robust
- The goal is to cool the lpGBT chips and keep them below 0°C
- Frame to be glued on the Pocofoam block inside the disk (opening in the carbon fiber sheet)
- It also makes the mounting of the Portcard easier
- Final Portcard dimensions will be larger to maximise overlap area with frame

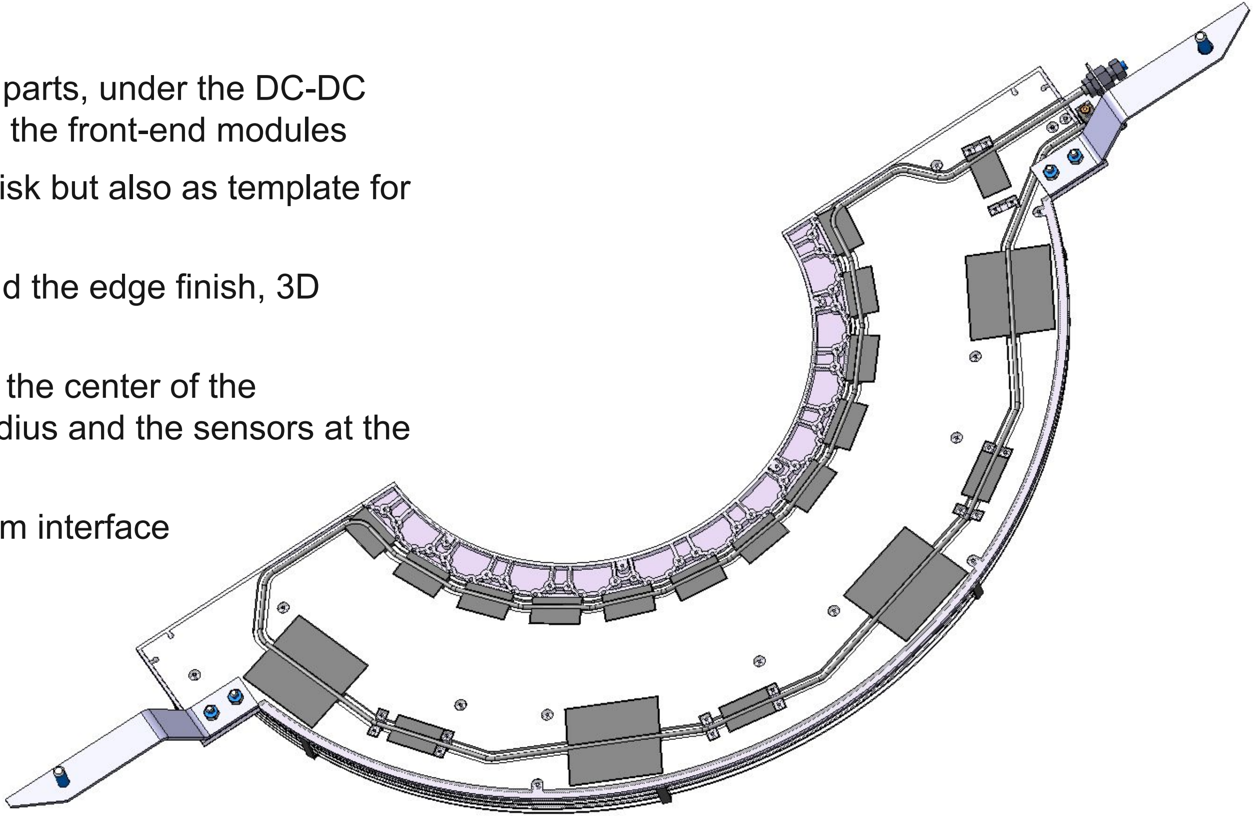




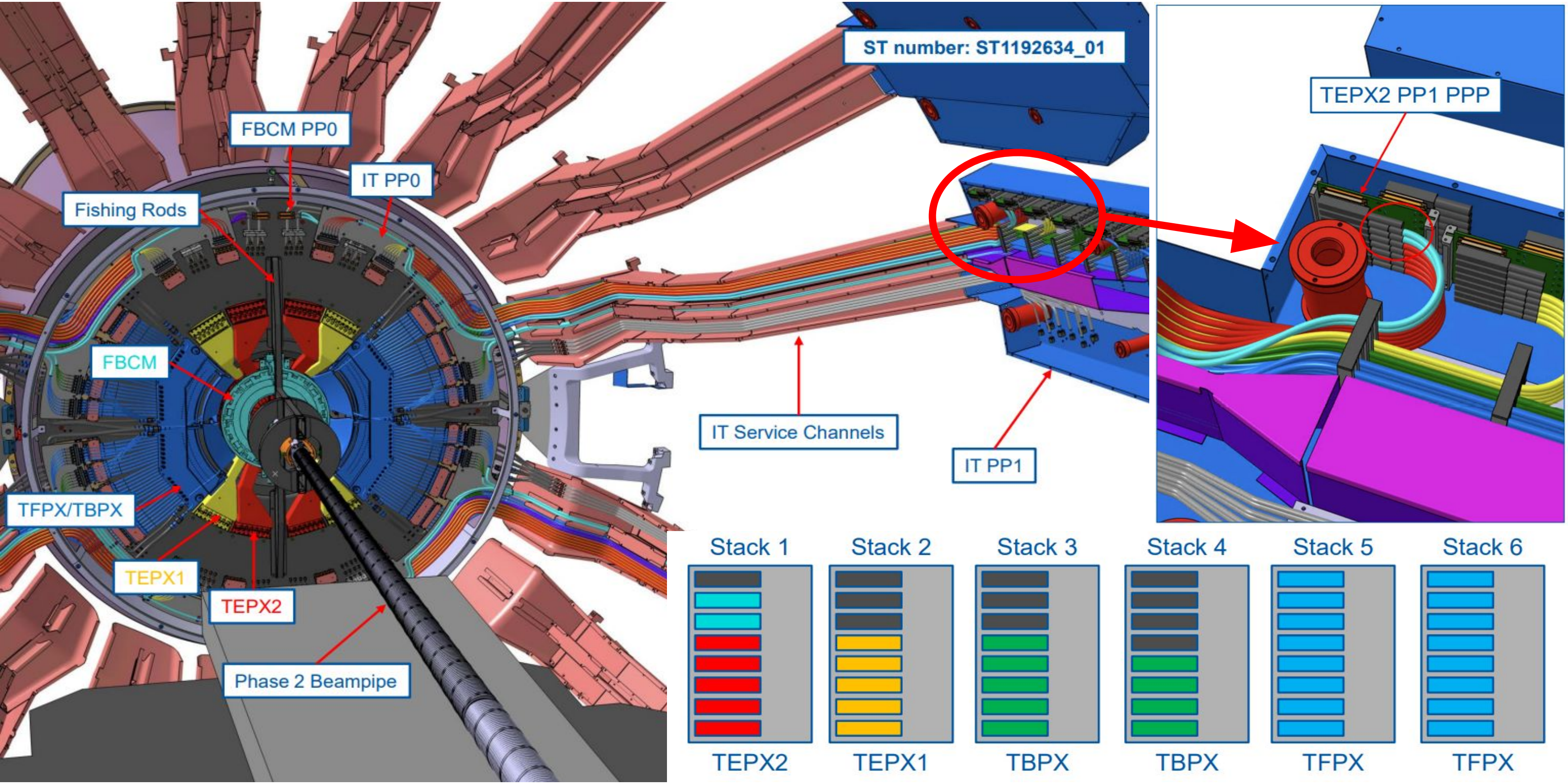
Support Structure

- Pocofoam only at sensitive parts, under the DC-DC modules, the portcards and the front-end modules
- Airex foam used to fill the disk but also as template for the building of the disk
- PPS used for the inserts and the edge finish, 3D printable resin material
- Pipe bent in order to match the center of the components at the outer radius and the sensors at the inner radius
- Hot dog design for pipe-foam interface



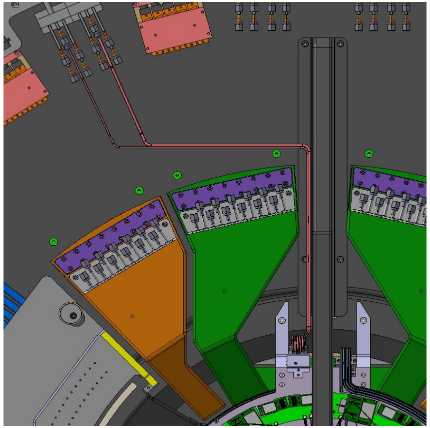


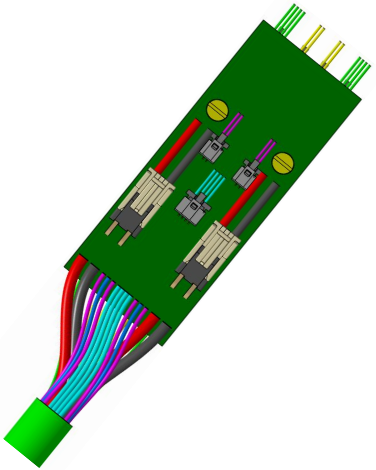
Integration

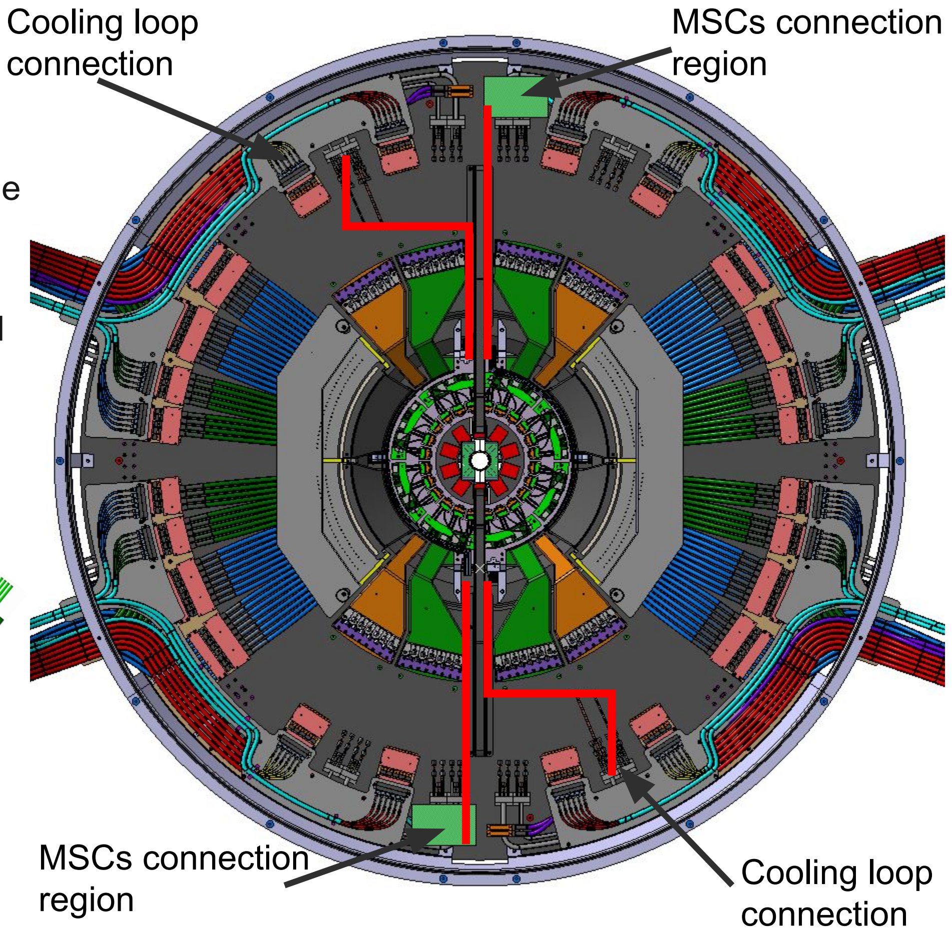


Integration

- Dedicated connection region for Multiservice Cables
- 2 turquoise multiservice cables at the top and 2 at the bottom plugging into the first of the PowerPatch-Panels in the PP0
- Cooling loop to be connected at the TEPX1 manifold
- Services along the fishing rod
- Filter boards at the MSCs connection regions to divide them into bundles



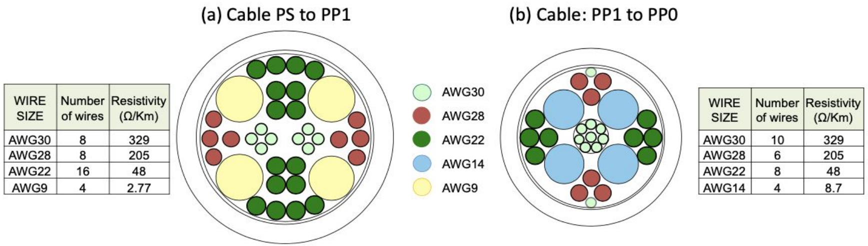




Integration

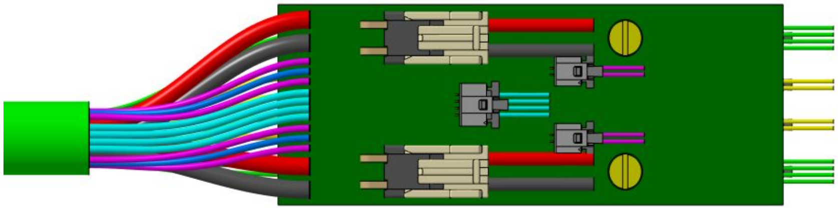
- One quarter of FBCM needs fit into 2 Inner Tracker Multi-Service Cables

Service	Type	Total # of wires	Wire Type	Available		Used	Free	Comment
FE power	LV	8	AWG22	16		8	0	LV and GND
Portcard power	LV	8	AWG14	8		8	0	LV and GND independent
HV return	LV	4	AWG22			4	0	can be together with LV GND but retain as option
FE HV	HV	12	AWG28	12		12	0	HV only, common return
Pre-heaters	LV	4	AWG22			4	0	similar to IT, 1 will do
T monitor	LV	16	AWG30	20		16	4	4W Pt100(0)



WIRE SIZE	Number of wires	Resistivity (Ω/Km)
AWG30	8	329
AWG28	8	205
AWG22	16	48
AWG9	4	2.77

WIRE SIZE	Number of wires	Resistivity (Ω/Km)
AWG30	10	329
AWG28	6	205
AWG22	8	48
AWG14	4	8.7



Example of a Filter Board