The CMS Fast Beam Condition Monitor (FBCM) for HL-LHC

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on behalf of the CMS Collaboration

16th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD23)
2023 Sept 25-29 @ Siena, Italy

2023-09-25

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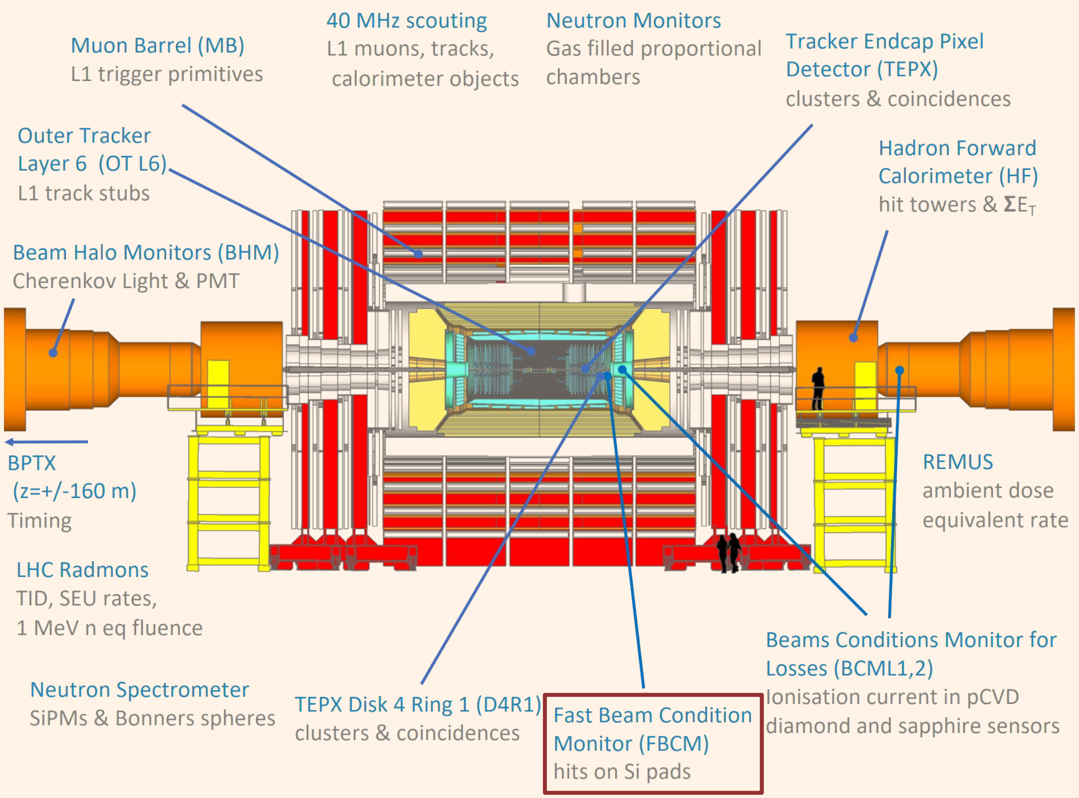
BRIL Upgrades for HL-LHC



BRIL: Beam Radiation, Instrumentation, and Luminosity

HL-LHC conditions

- ~10x increase in LHC's design luminosity
  - $N = \mathcal{L} \cdot \sigma$
- Up to 200 **interactions per bunch-crossing** (pileup)
  - ≈60 in Run-3

BRIL Deliverables

- **Luminosity**
  - < 1% offline
  - < 2% online
- Beam-induced background (**BIB**) monitoring
- Active protection from dangerous beam loss events (beam abort)
- Relative beam timing and technical triggers
- Monitoring & simulation of radiation environment in CMS cavern

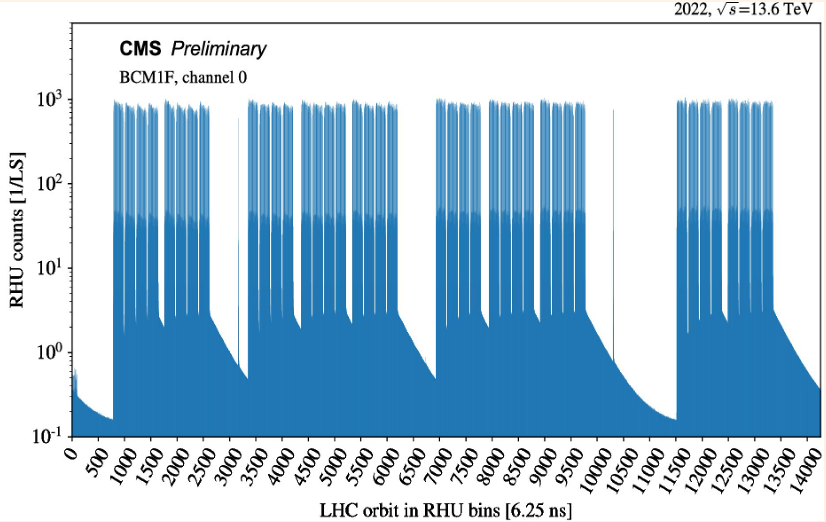
Why a Dedicated Luminometer?

Standalone instrument with **maximum availability** required for lumi & BIB measurement

- Luminosity & beam-induced background **required** anytime beams are **circulating**
  - LHC relies on **luminosity measurement** to deliver and optimize collisions at CMS
  - CMS relies on **BIB monitoring** to guarantee the safe operation of subsystems
  - Special conditions (e.g. **machine commissioning** and **development**) require luminosity and BIB publications while the rest of CMS may not be in operation

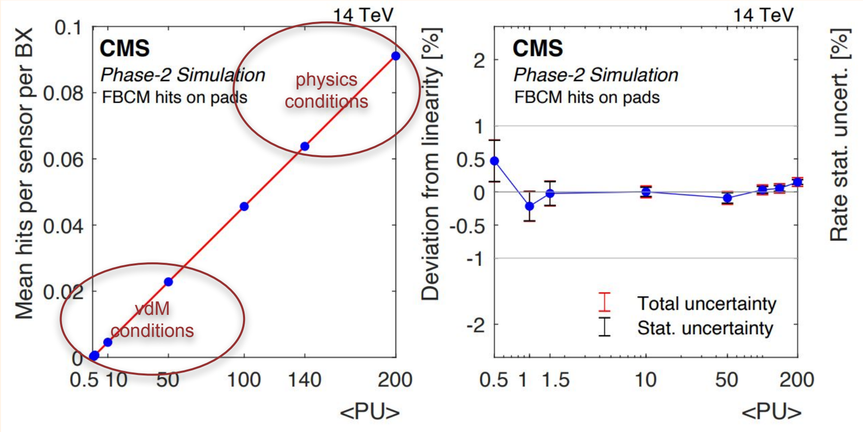
Infrastructure and **operational** independence

- Must be able to operate regardless of status of sub-systems and central DAQ & trigger services
  - Dedicated luminosity data acquisition system
- Flexibility and frequency of operational changes
  - Calibrations, threshold adjustments, HV scans or setpoint changes, etc.



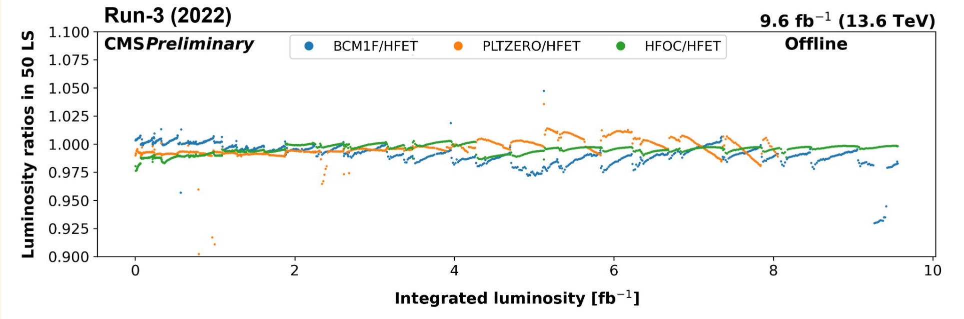
FBCM Requirements

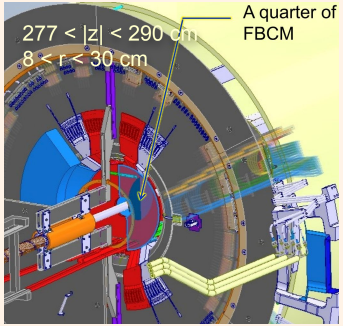
- Optimized for a **linear response** over the required **dynamic range**
  - **Precise calibration** of luminometers requires low-pileup (vdM) running conditions
    - Requires sufficient **statistical precision**
  - **Propagation** of low-pileup (vdM) calibration to physics data-taking conditions
    - Requires small **dynamic inefficiencies** up to maximum pileup planned for HL-LHC
    - Requires tracking of **long-term variations** in luminometer performance over data-taking period

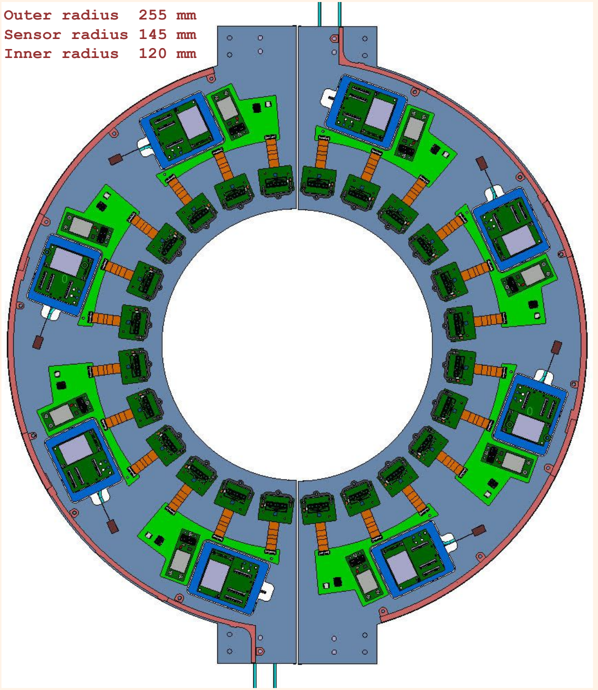


FBCM Concept

- Concept based on current (Run-3) **BCM1F** detector
  - New front-end & back-end electronics
  - New readout scheme
  - More channels (48 → 288)
  - C_6F_{14} → CO_2 cooling (-35°C)
- Bunch-by-bunch (40 MHz) luminosity measurement
  - Based on "**zero-counting**" algorithm from hits on Si-pad detectors
- **Sub-bunch-crossing** timing resolution
  - Enables beam-induced background measurement







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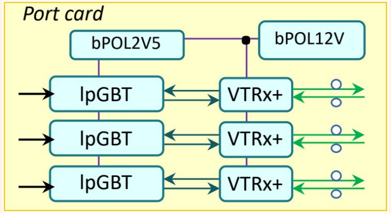
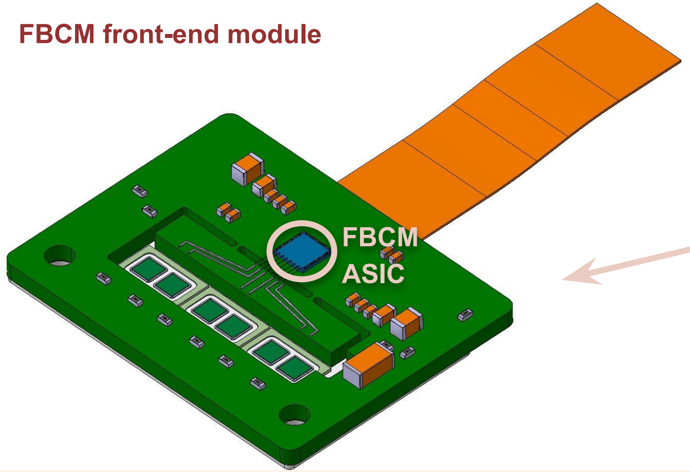
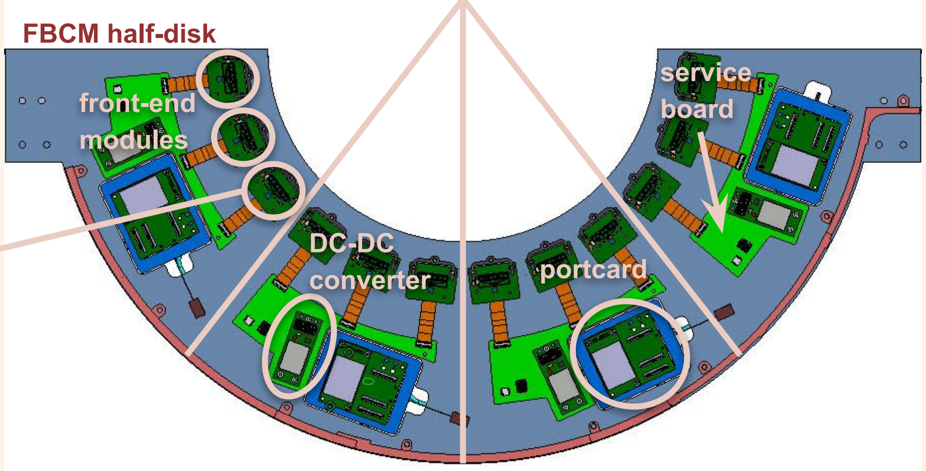
FBCM Design

- Symmetric **Modular** Design
  - Avoids single points of failure and simplifies maintenance
- 4 mechanically-identical **half-disks** (2x per end of CMS)
  - Each half-disk composed of 4x identical **service quadrants**
- Each **service quadrant** composed of identical components
  - 3x **front-end modules** (1x ASIC and 6x Si-pad sensors)
  - 1x **service board** (1x DC-DC converter and 1x Inner Tracker portcard [3x lpGBT & 3x VTRx+])



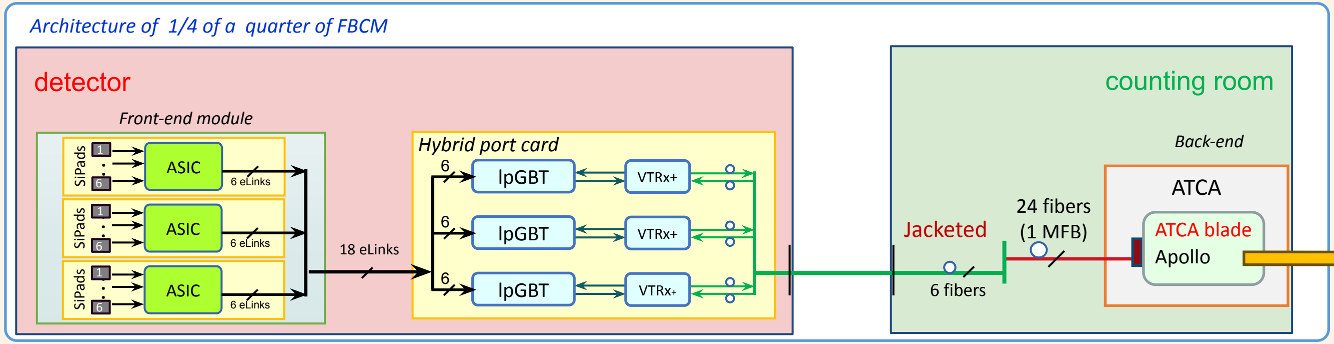
lpGBT = Low Power GigaBit Transceiver
VTRx+ = Versatile Link Plus Transceiver

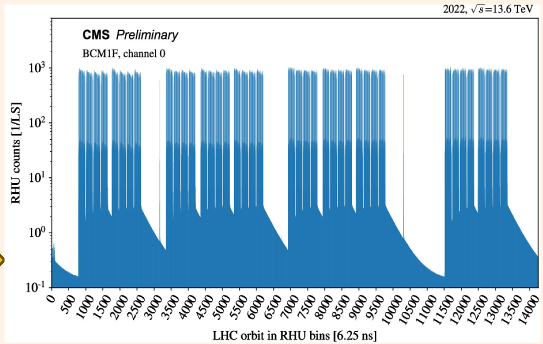




FBCM Read-out

- Analog signal from sensors
  - Low voltage pulse via short low-capacitance wire-bonds
- ASIC: Fast amplifier and comparator
  - Discriminate signal and outputs as a binary differential signal via e-links
- Portcard: lpGBT (transceiver) & VTRx+ (optical interface)
  - lpGBT samples binary signal, packs it into frames, and outputs via VTRx+ electro-optical interface
- Back-end Apollo FPGA board
  - Data is unpacked and ToA & ToT measured & aggregated into sub-bunch-crossing histograms



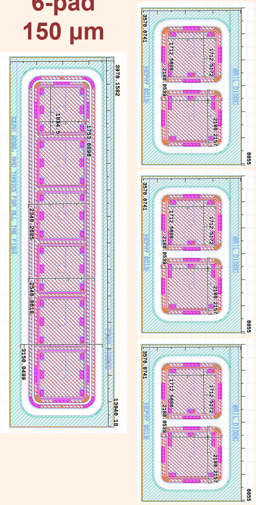


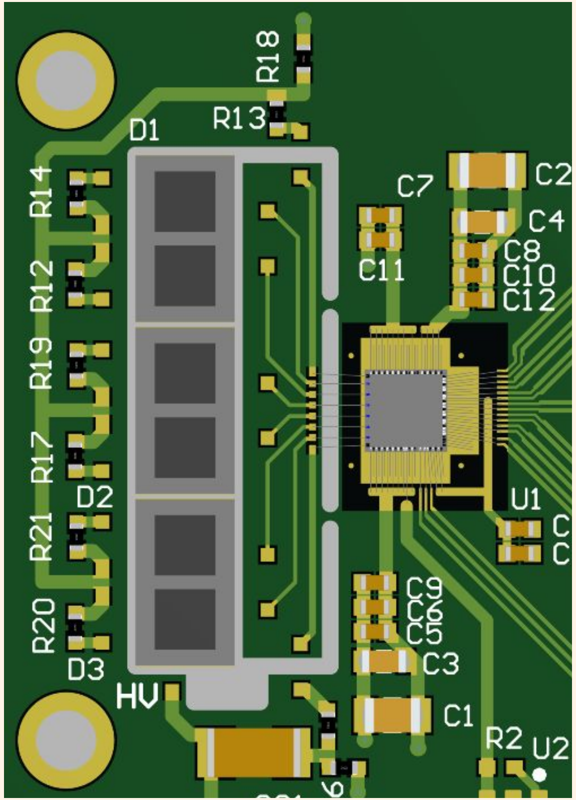
FBCM Sensors

- Expected fluence at FBCM sensor location
  - ≈2.5×10^{15} n_{eq} /cm² for 3000 /fb
    - Outer Tracker: ≈1.5×10^{15}
    - Inner Tracker: ≈1×10^{16}
  - Planning for **replacement** after about 1500 /fb
- Two types of sensors being considered
  - **290 µm** 3x 2-pad sensors (same as Run-3 BCM1F)
    - Produced on Outer Tracker PS-s wafers
    - Better S/N but high leakage current
  - **150 µm** 1x 6-pad sensors
    - Produced on Inner Tracker wafers
    - Lower S/N but more rad-hard
    - Common GND ring to limit sensitive volume
  - Final choice to be made after **test beam with ASIC**

6-pad 150 µm

2-pad 290 µm





FBCM test board with ASIC and sensors

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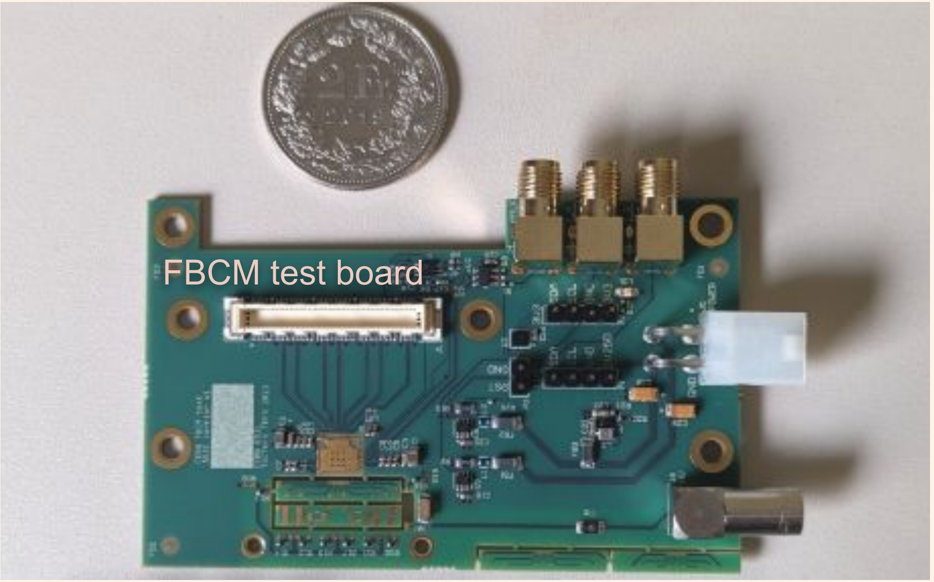
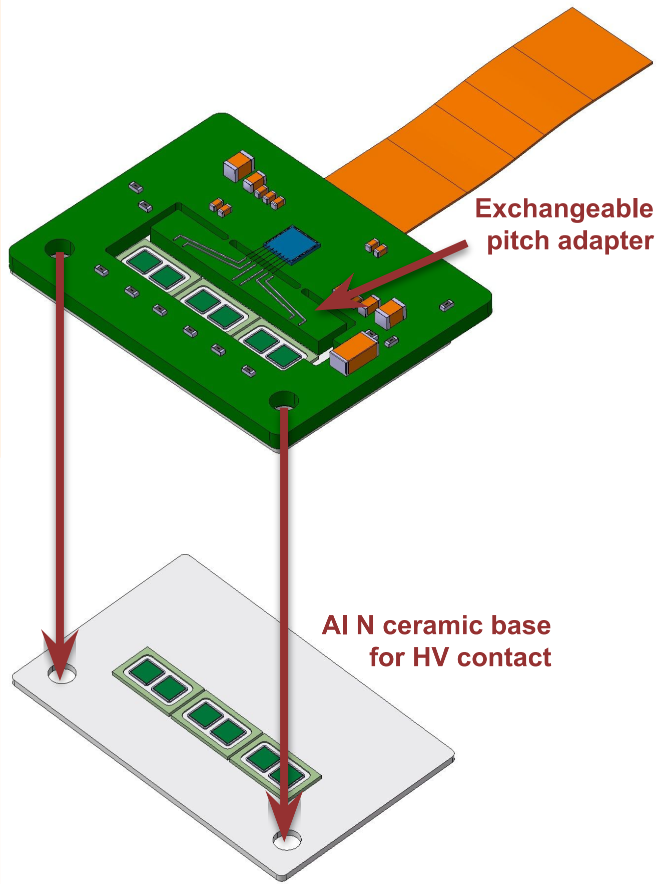
Front-end Hybrid

- **Thermally-optimised** front-end hybrid design
  - Based on Aluminium Nitride baseplate with metallization
- Front-end testboard **on hand**
  - Optimized for radiation length (material budget)



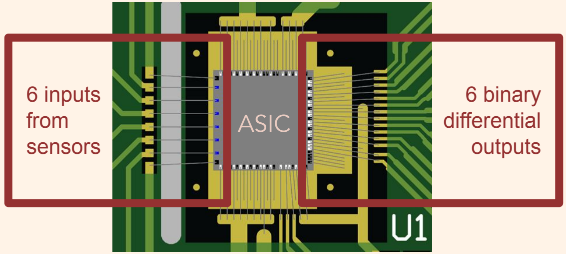


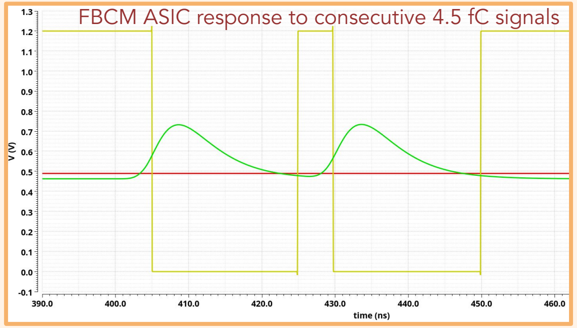
FBCM ASIC

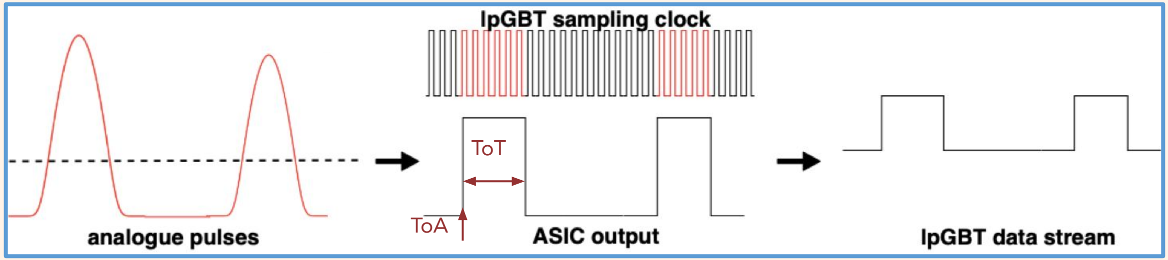
<u>Radiation-hard 65 nm front-end ASIC</u>

- 3×3 mm², wire-bonded
- 6 channels per chip, SLVS output
- Trigger-less (asynchronous) readout
- Electronic noise below 900 e^-
- Fast amplifier and comparator
  - Fast return to baseline after hit with multiple MIPs (150 fC)
  - Double-hit resolution after discrimination: 25 ns
- Expected dose & fluence:
  - 200 Mrad and 2.5×10^{15} n_{eq}/cm^2
  - SEU-protected I²C register block

FBCM ASIC top view on test board







SLVS = Scalable Low-Voltage Signal
SEU = Single Event Upset (bitflip)

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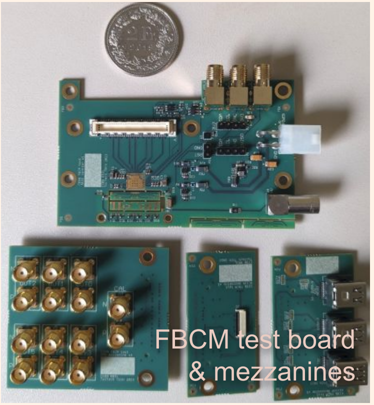
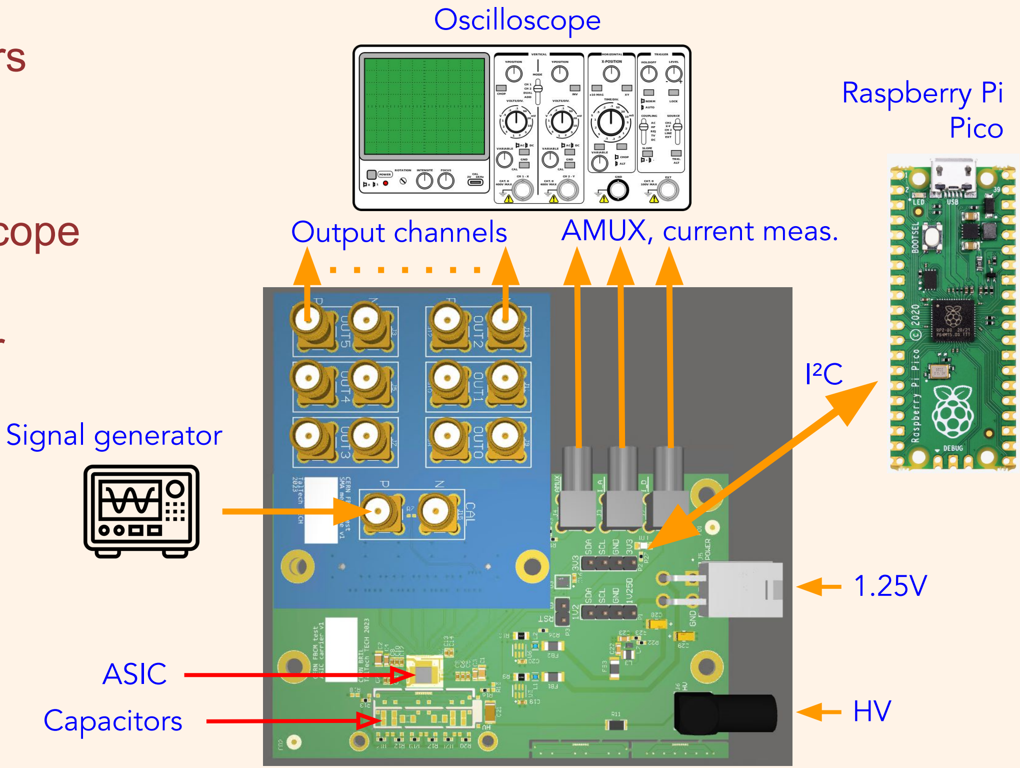
FBCM ASIC Testing

Stage 1: bare ASIC (for several chips)

- ASIC validation and initial qualification
  - At first, capacitors to emulate sensors
- Power (1.25V) from lab power supply
- I²C configuration using Raspberry Pi
- Analog signal measurement with oscilloscope
- Current consumption measurement
- Calibration strobe from a signal generator





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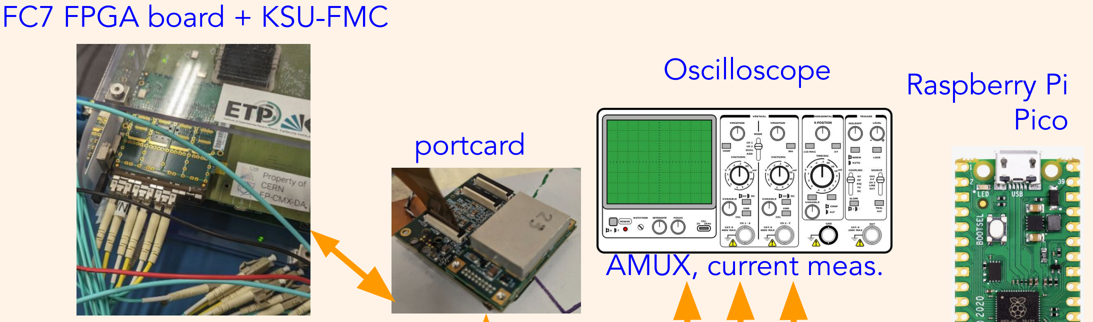
FBCM Sensor & Firmware Testing

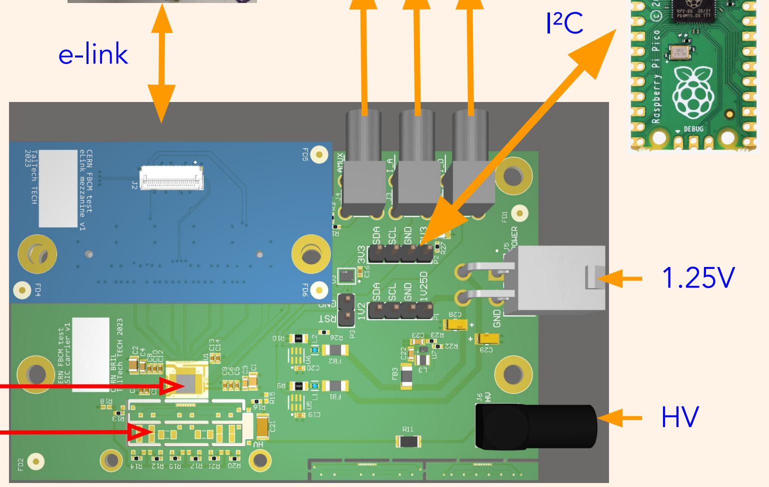
Stage 2: Sensor and FW testing

- Sensors mounted and wire-bonded
- Galvanic e-link connection to back-end
- Back-end firmware on FC7 FPGA board
- Power (1.25V) from lab power supply
- I²C configuration using Raspberry Pi
- Calibration strobe from FPGA



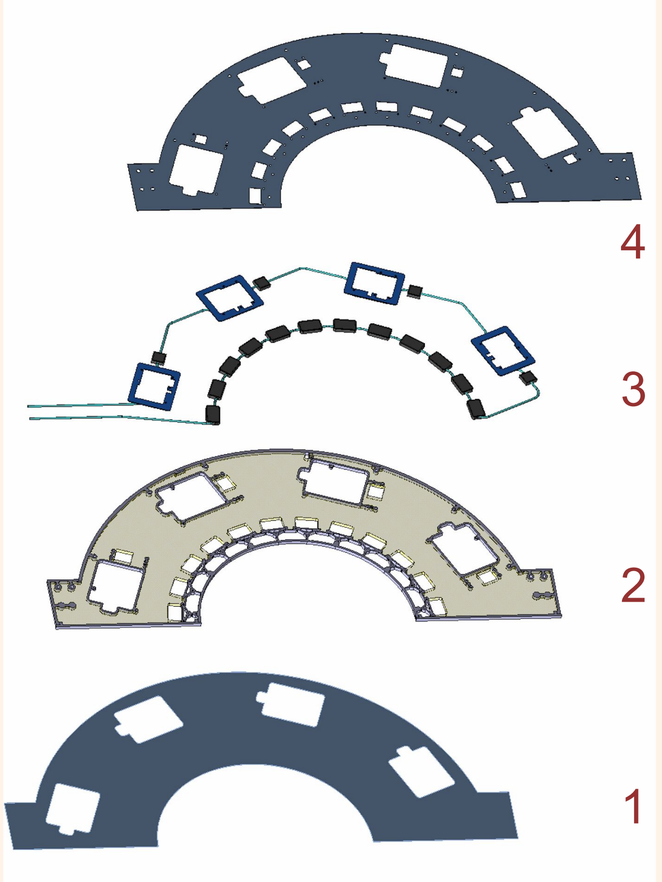
Stage 3: Test beam (system tests and validation)

- Test and read-out of the system with radioactive source
- Unirradiated and irradiated sensors will be tested



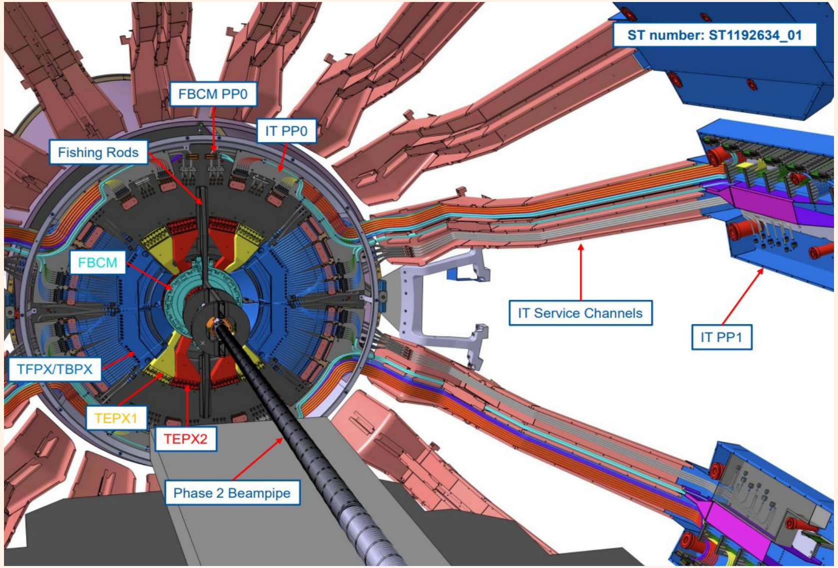
Building Process

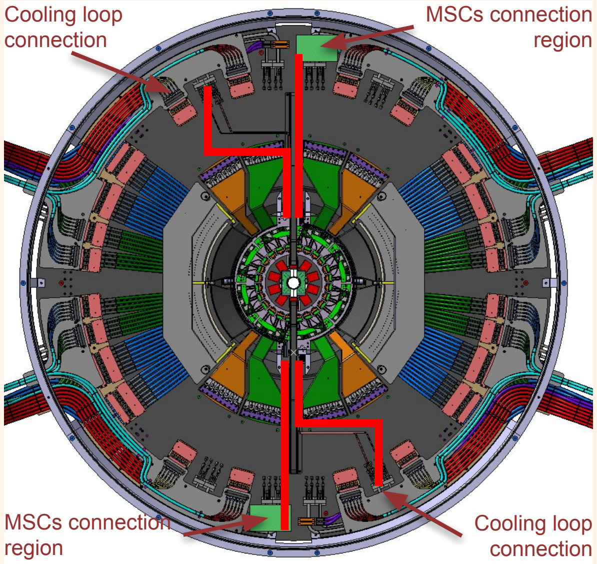
1. Top carbon fibre sheet is placed on the vacuum plate used for building the disk
2. Airex foam is glued on carbon fibre sheet and used as template in next steps
3. Pocofoam blocks are added into cut-outs and glued
   a. Everything machined to the right shapes
   b. Grooves & holes are drilled
   c. Pipe is glued into groove (thin layer of diamond-mixed epoxy)
   d. Everything is flattened via vacuum bag
4. Bottom carbon fibre sheet is glued on top to finish building the disk



FBCM Integration

- Minimal connections per half-disk
  - Each attached with two screws, single optical connector, and two Multiservice Cables
- Dedicated connection region for Multiservice Cables
  - Multiservice cables plug into Power Patch-Panels
- Cooling loop to be connected at the End-cap Pixel manifold



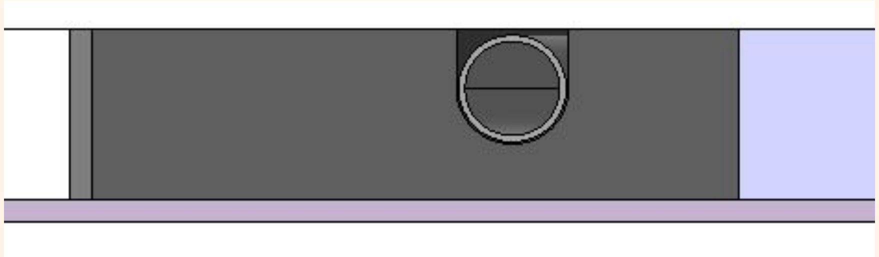


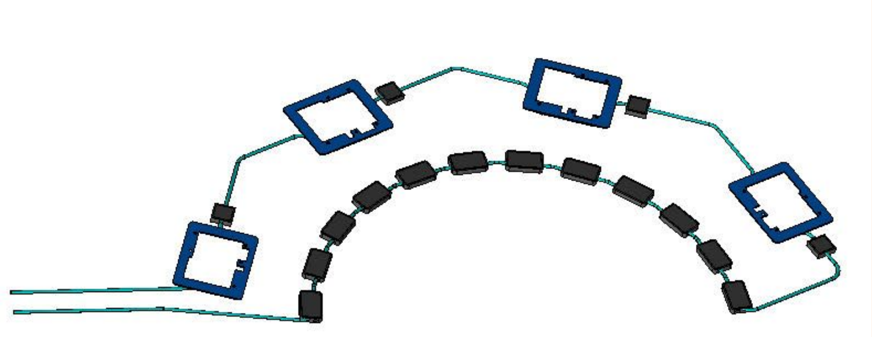
Summary

- CMS HL-LHC strategy
  - Multiple **independently-calibrated** luminometers
  - Dedicated, standalone instrument provides **robustness in operation** and **luminometer characterization**
- Fast Beam Condition Monitor (FBCM) is under development and prototyping
  - **On track** for Phase-2 upgrade (HL-LHC)
  - **Fast front-end** with **dedicated ASIC and sensors**
  - Instrumental for HL-LHC luminosity measurement **target uncertainty** (2% online; <1% offline)
- FBCM design
  - **Reliable** and **highly modular** system
  - Designed for **robustness** and **maintainability**
  - Uses **standard** and **tested** HL-LHC radiation-hard components
- Testing and characterization of FBCM
  - Currently in **testing** and **prototyping** phase
  - Electronic design of the front-end test system **ready**
  - Several stages planned for **testing** of ASIC, sensors, firmware

FBCM Mechanics: Support Structure

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





Zero-Counting Method

- Assume number of hits per bunch-crossing is described by a Poisson distribution
  - Probability of a certain number of hits: $p(n) = (\mu^n \cdot e^{-\mu}) / n!$
    - Where μ is the mean of the distribution
- Assume that luminosity is proportional to μ
- Probability that there is no hit ($p_0 = e^{-\mu}$) is used to determine the mean value μ
  - $\mu = -\ln(p_0)$
- Given low occupancy, zero-counting method yields relative luminosity