CERN CMS
Beam Radiation, Instrumentation and
Luminosity (BRIL) group

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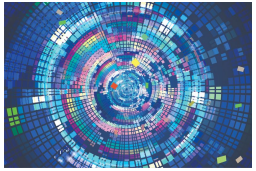
Electronics design and testing of the CMS Fast Beam Condition Monitor for HL-LHC



Technology & Instrumentation in Particle Physics (TIPP 2023)
September 7th 2023, Cape Town

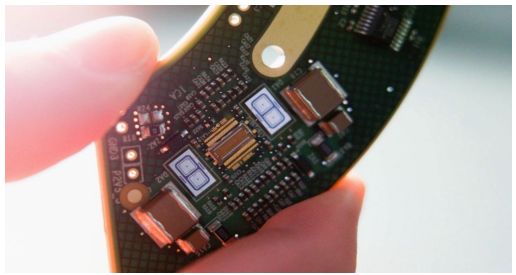
Need for a new Dedicated Luminometer

Dedicated standalone luminometer in CMS measures beam luminosity and beam-induced background (BIB) independent of other infrastructure.

- Always on when beams are present
- Orthogonal systematic error to other CMS subsystems

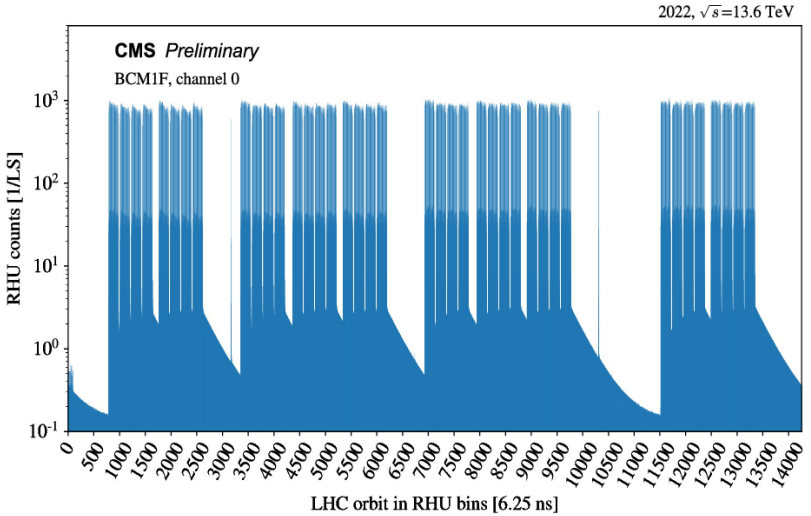
Previous luminometer BCM1F designed for BIB and luminosity measurement has been successfully used in LHC Run 2 & 3

- Fast, asynchronous front-end ASIC
- Simple design: analogue read-out, signal processing at the back end (BE)
- Run-3 design based entirely on Si-pad detectors
  - Designed for 1.5x10^{15} 1 MeV n eq fluence
  - Excellent linearity



There is a strong need for a new upgraded independent luminometer for HL-LHC

- Per-bunch luminosity measurement at full 40 MHz rate
- Improved sub-bunch timing resolution allowing BIB measurement
- Ambitious luminosity precision goal for Phase-2 (2% online and <1% offline)

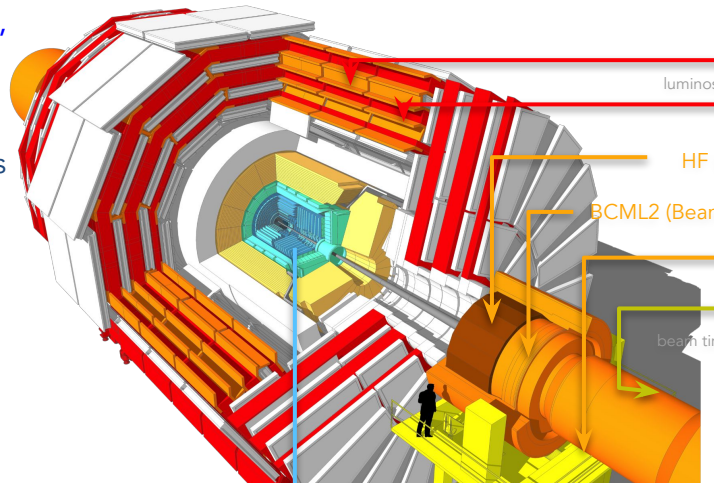


Example histogram of measured BCM1F raw counts integrated over 1 lumi section (LS~23 s). The "afterglow" tails following every bunch train are clearly visible. Detector has timing resolution of 4 bins in each bunch-crossing

Fast Beam Condition Monitor (FBCM)

Fast Beam Condition Monitor is the next dedicated luminometer constructed by the Beam Radiation, Instrumentation and Luminosity (BRIL) group of CMS

- Planned for Phase-2 upgrade (HL-LHC)
- Upgrade and the successor of previous luminometer BCM1F
- New front-end and back-end electronics
- More sensors and measurement channels
  - 48 in BCM1F vs. 288 in FBCM
- CO_2 cooling for components
- Binary (semi-digital) signals instead of analog



40 MHz trigger scouting
luminosity (L1 muons, tracks, calorimeter objects)
Muon Barrel
luminosity (L1 trigger primitives)
HF (Hadronic Forward Calorimeter)
luminosity (quartz fibers)
BCML2 (Beam Condition Monitor for Losses)
beam losses (sapphire sensors)
BHM (Beam Halo Monitor)
beam-induced background (quartz bars)
BPTX (Beam Pick-up Timing)
beam timing and phase (electromagnetic pickups)

FBCM (Fast Beam Condition Monitor)
luminosity (Si pad zero-counting)
BCML1 (Beam Condition Monitor for Losses)
beam losses (pCVD diamond sensors)
TPEX (Tracker Endcap Pixel Detector)
luminosity (Si pixel cluster counting)
OT (Outer Tracker Layer 6)
luminosity (Si strip sensor coincidences)

Fast Beam Condition Monitor : Concept

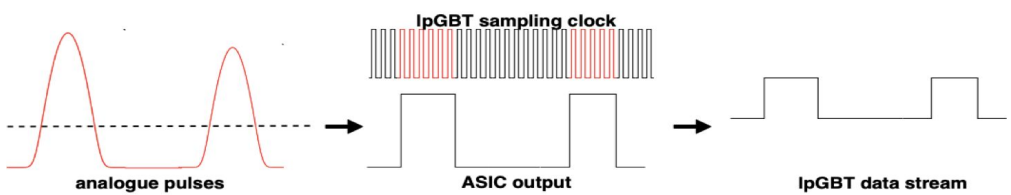
Fast Beam Condition Monitor (FBCM) aims at higher performance for HL-LHC

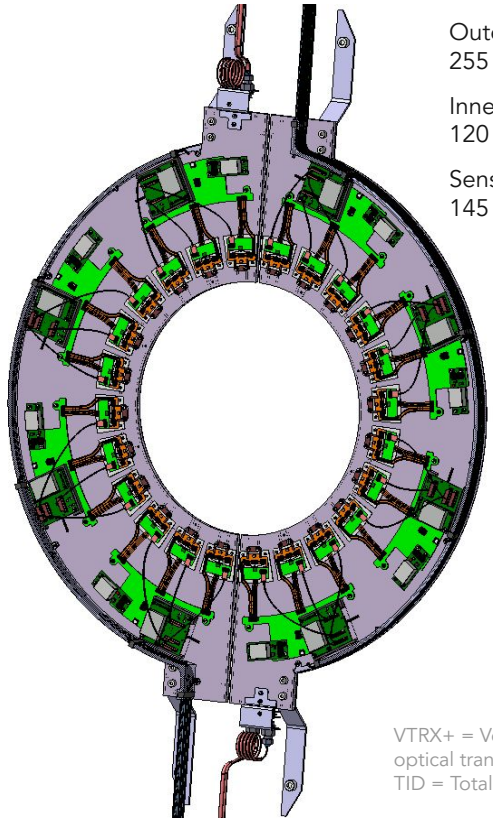
Simple front-end (FE) electronics system with dedicated rad-hard 65 nm ASIC
- Binary output starting at time of arrival (ToA) and lasting for time over threshold (ToT) sampled upstream by a low power gigabit transceiver (lpGBT)
- Signal processing in FPGA-based back-end (CERN Apollo board)

Measuring BIB & luminosity by applying the 'zero-counting' algorithm with hits on Si-pad detectors
- Data collected in histograms in the back-end

Modernising the electronics (system architecture) - design uses standard HL-LHC electronics components for high-radiation environment: lpGBT, VTRX+ & DC-DC converters
- Widely used across CMS and qualified to the radiation levels at the FBCM location (expected 1 MeV n eq fluence is ~2.2×10^{15} cm^{-2} for 4000 fb^{-1}, TID(Si) is ~109 Mrad)

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, and to ease the replacement of failing components





Outer Radius R = 255 mm

Inner Radius r = 120 mm

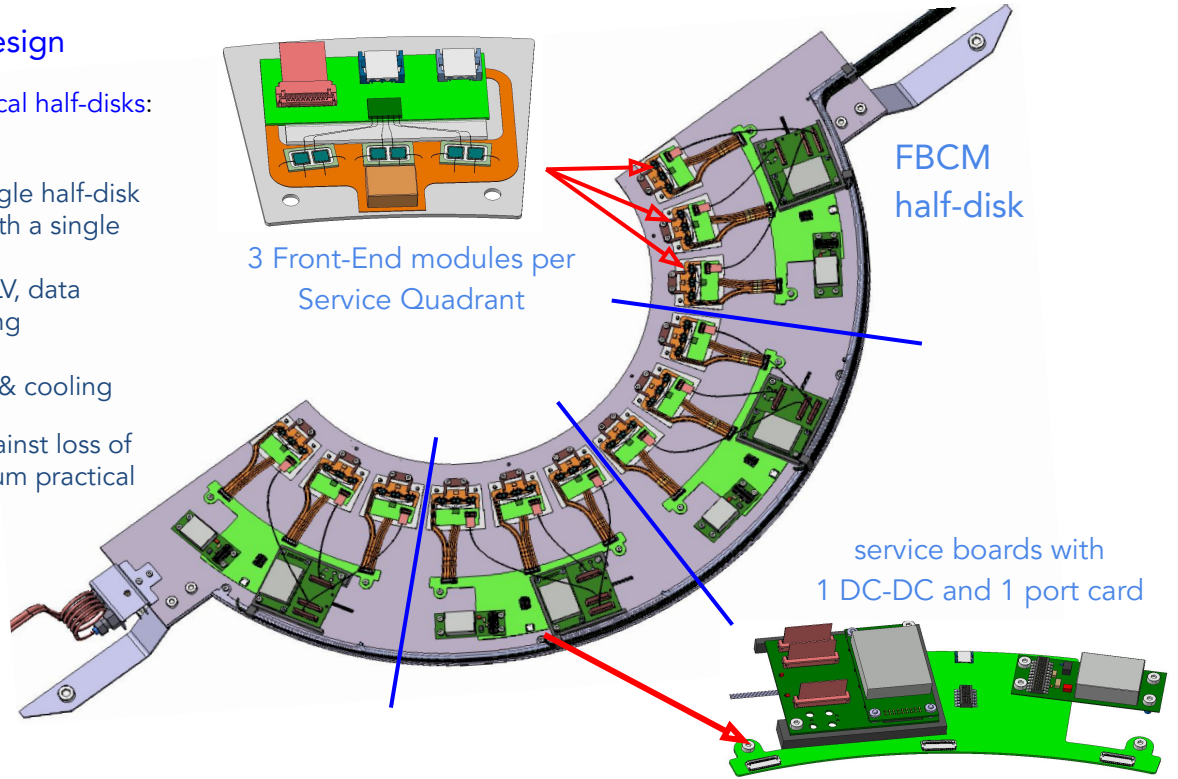
Sensors radius r = 145 mm

VTRX+ = Versatile Link + optical transceiver
TID = Total Ionizing Dose

FBCM System Design

FBCM uses a fully symmetric modular design

- Full FBCM system is 4 identical mechanical half-disks: 2 per each end of CMS
- 4 identical service quadrants within a single half-disk
  - 3 identical front-end modules with a single FBCM ASIC & 6 Si-pads
  - Service board providing FE HV/LV, data read-out, slow-control, monitoring
  - DC/DC converter and portcard
  - Supported by common services & cooling
- FBCM performance is highly tolerant against loss of individual channels, yet maintain maximum practical granularity in services
- CO_2 cooling for sensors, ASICs, port cards and DC-DC converters



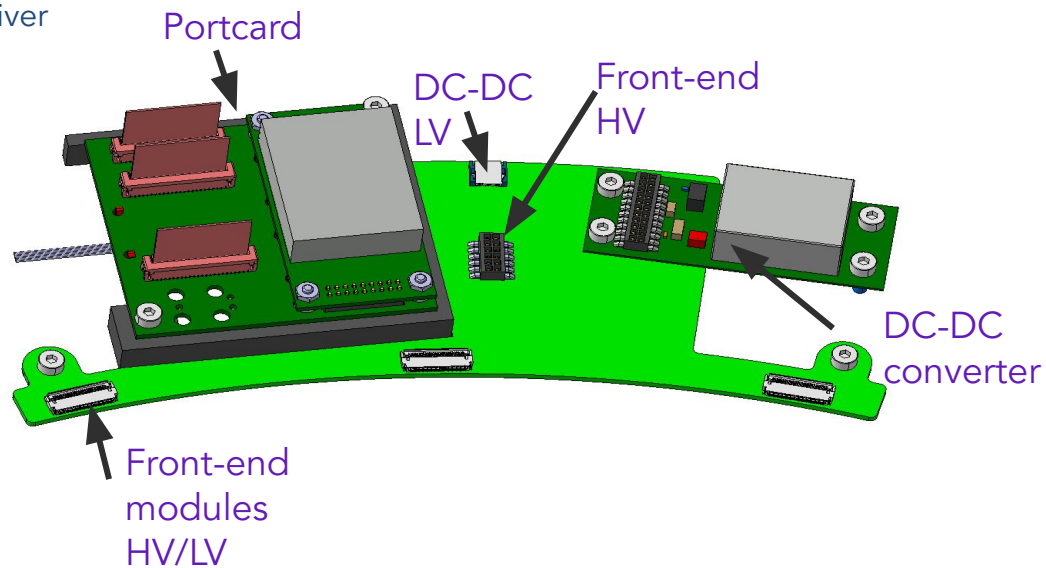
Service board

Service board contains:

- IT portcard
  - 3 lpGBT: low-power gigabit transceiver
  - 3 VTRx+: Versatile Link + optical transceiver
  - E-links to front-end modules
  - bPOL12V, bPOL2V5: DC-DC converters
- Connectors for HV/LV power of front-end modules
- DC-DC converter (bPOL12V) for 1.2V front-end power

All components standard rad-hard HL-LHC

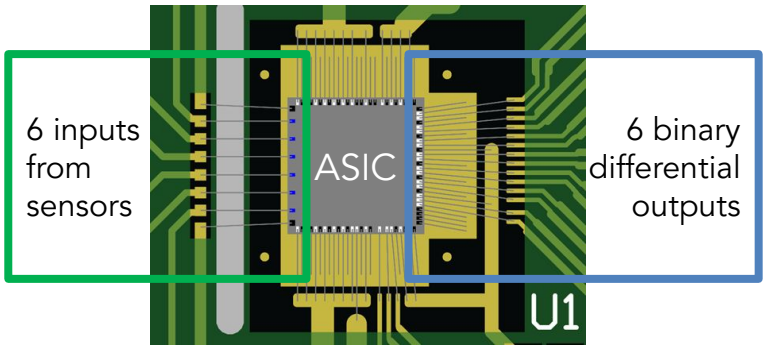
- lpGBT, VTRx+
- bPOL12V, bPOL2V5
- Qualified connectors



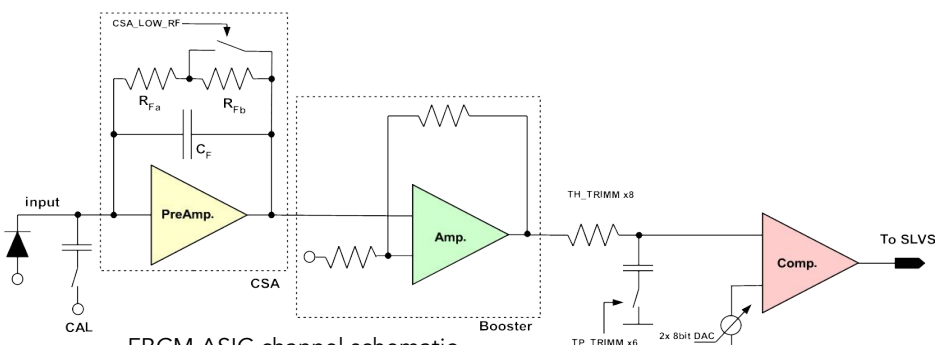
ASIC

Radiation-hard 65 nm binary front-end ASIC: 200 Mrad and 2.5x10^{15}n/cm^2

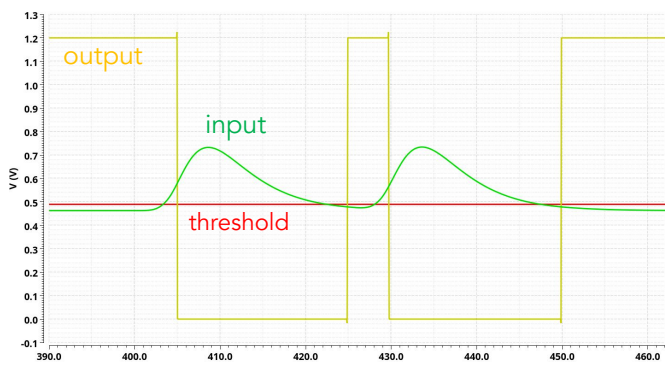
- Fast amplifier and comparator (sensor signal to threshold)
- Electronic noise below 900 e-
- Double hit resolution after discrimination: 25 ns
- Fast return to baseline after hit with multiple MIPs (150 fC)
- 6 channels per chip, SLVS output
- Trigger-less (asynchronous) readout
- SEU-protected I2C register block for ASIC configuration
- 3x3 mm^2, wire-bonded



FBCM ASIC top view on test board



FBCM ASIC channel schematic



FBCM ASIC response to two consecutive 4.5fC signals

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

Sensors

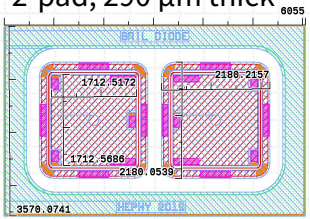
At FBCM sensor location expected 1 MeV n eq fluence is about 2.5×10^{15} for 3000 fb^{-1} (outer tracker: 1.5×10^{15}; inner tracker: 1×10^{16}), planning for replacement after about 1500 fb^{-1}

Two types of sensors are available for tests:

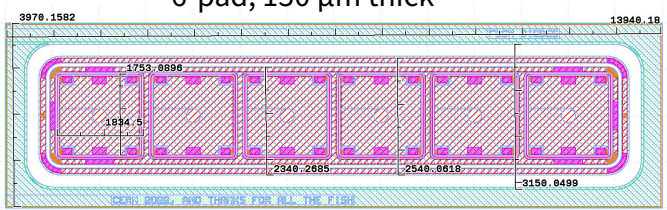
- 290 µm (same as used in Run 3 BCM1F system)
  - better S/N (pre-radiation: ~35, after 1×10^{15}: 10.7)
  - high leakage current when irradiated → high shot noise
- 150 µm (need to validate these sensors for use in final system)
  - more rad-hard but lower signals
  - common GND ring to limit sensitive volume
  - worse S/N (pre-radiation: 17, after 2.5×10^{15}: ~8)
  - lower leakage current, thus shot noise

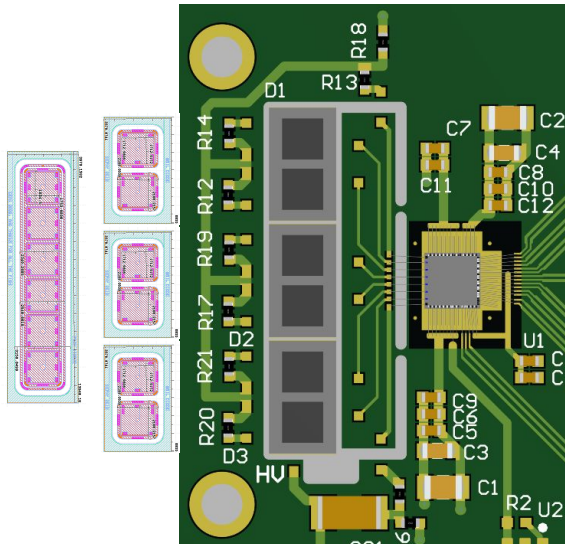
Final choice after test beam with ASIC and both types of irradiated sensors

2-pad, 290 µm thick



6-pad, 150 µm thick



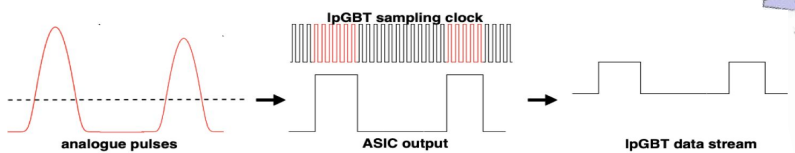


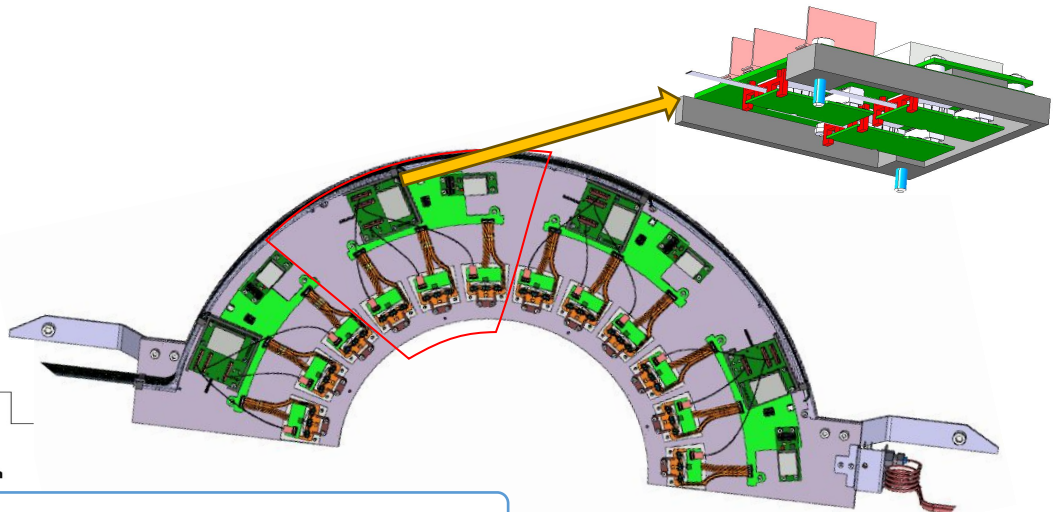
FBCM test board with ASIC and sensors

Read-out chain

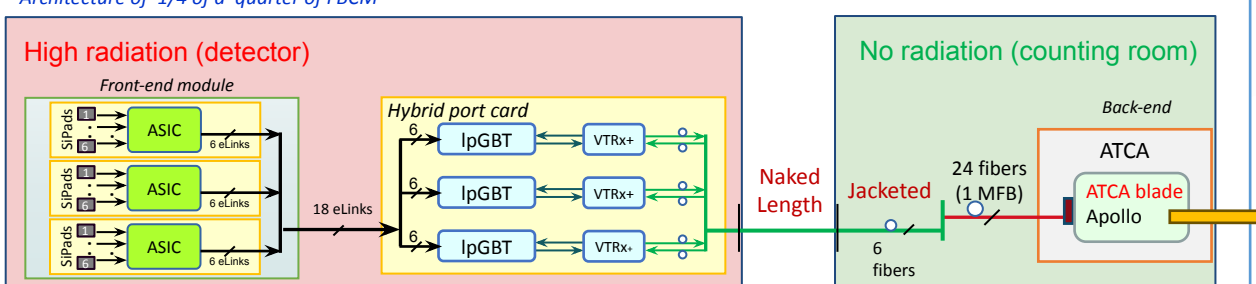
Data-taking path:

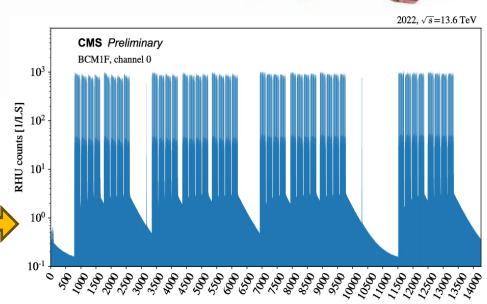
1. Analog signal from sensors
2. ASIC comparator binary output
3. lpGBT (transceiver) & VTRx+ (optical interface)
4. Optical fiber to counting room
5. Back-end Apollo FPGA board
6. ToA and ToT sub-bunch-crossing histograms





Architecture of 1/4 of a quarter of FBCM

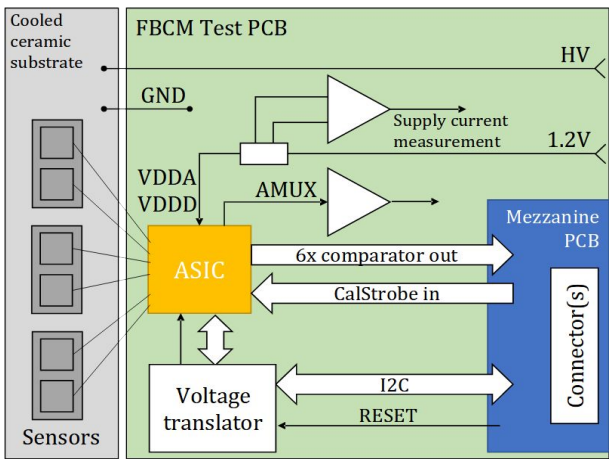




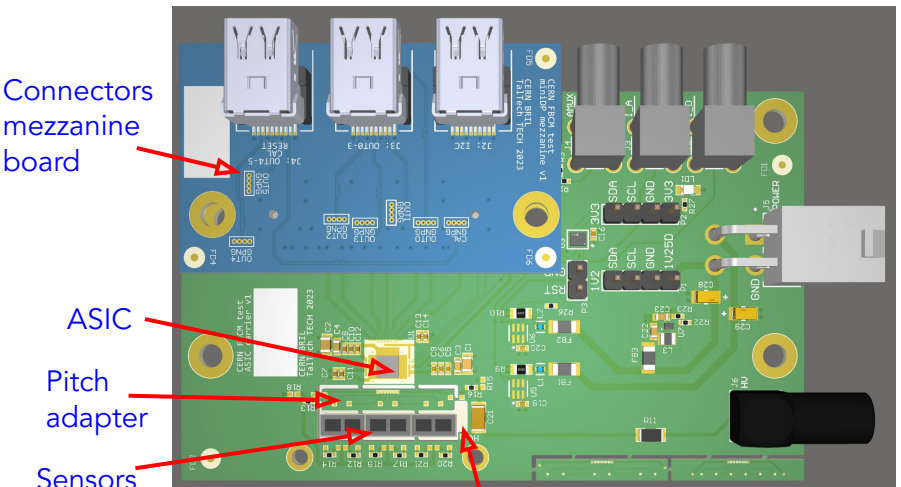
Test board

BRIL and TalTech are collaborating in the development of the test system for FBCM:

- Carrier board with ASIC, power, measurement, sensor connections
- AlN plate with sensor bias (HV) and good cooling properties
- Replaceable mezzanine board to allow connection to:
  - Back-end via galvanic links
  - Back-end via lpGBT optical links
  - Oscilloscope via SMA break-out



FBCM test board architecture



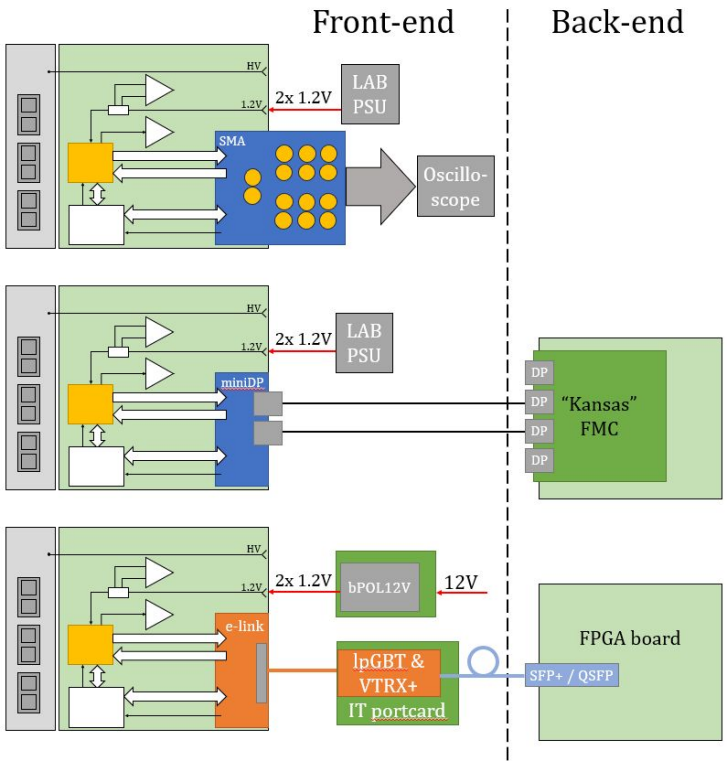
Test plan

Test system is developed to support all testing needs throughout the project lifetime

2023 Stage 1: Lab bare ASIC tests (for several chips):
- ASIC validation and initial qualification using test points and AMUX output
  - I2C configuration using Raspberry PI Pico
  - Calibration strobe (Raspberry PI Pico, pulse generator, scope)

2023->2024 Stage 2: Lab ASIC + sensor + firmware test:
- ASIC testing with back-end FPGA firmware
- Galvanic connection (miniDP)
- Use radioactive source, check spectra with the scope
- Test with lpGBT links (when available)

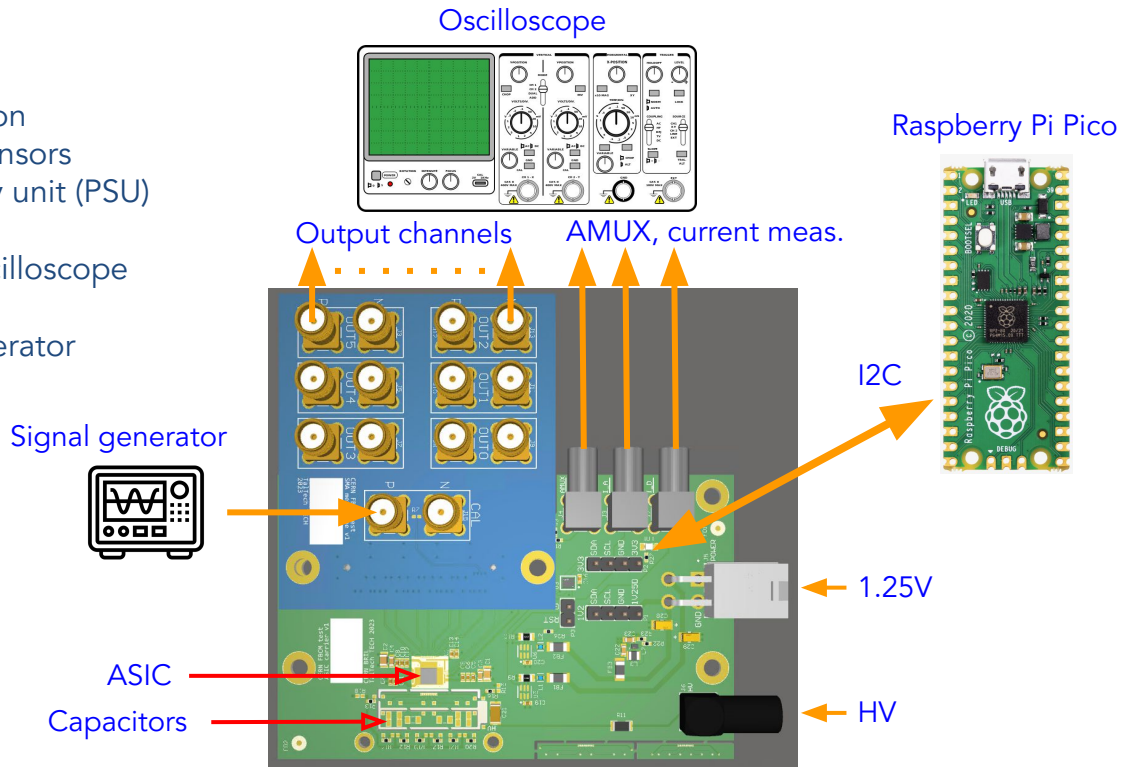
2024 Stage 3: test beam ASIC + sensor test + firmware:
- Qualification of ASIC & sensors before and after irradiation
- Gradually increase complexity of the system, approaching final design
  - DC-DC powering
  - Full read-out chain with lpGBT and VTRx+
  - I2C and reset via portcard
  - Firmware to decode lpGBT dataflow
  - Histogramming in the firmware
  - ToT monitoring



ASIC testing setup

Setup for initial ASIC testing

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



Sensor and firmware test setup

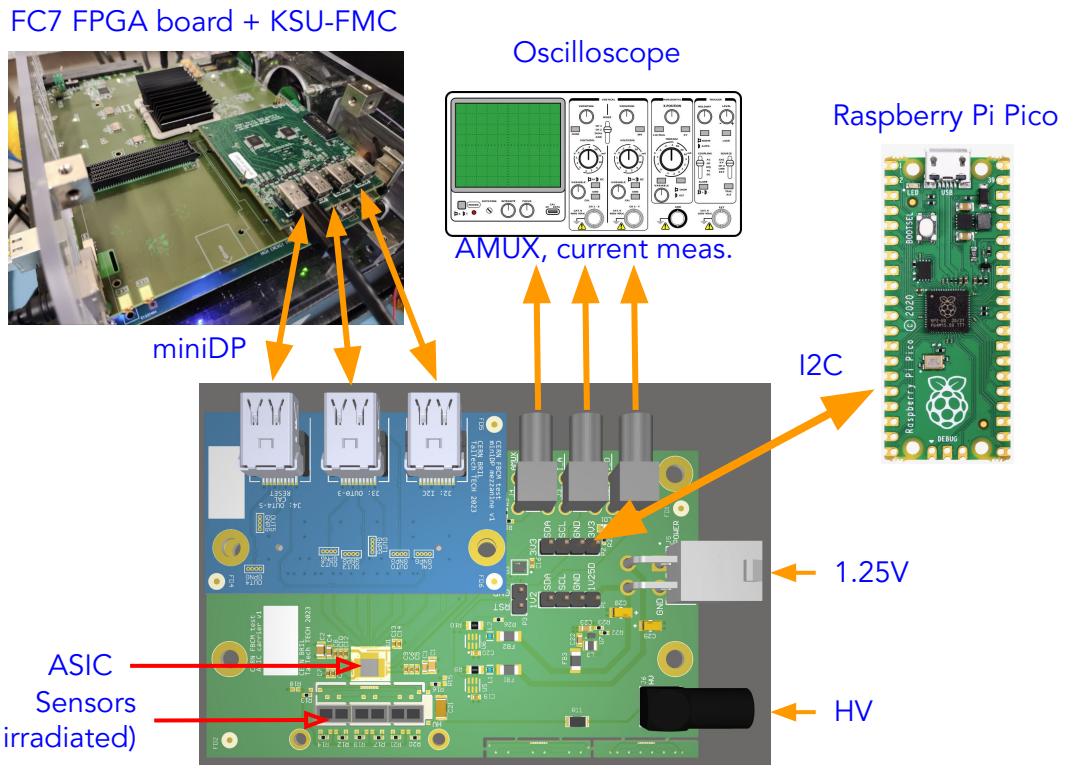
Setup for sensor and FW testing

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

System tests and validation with test beam

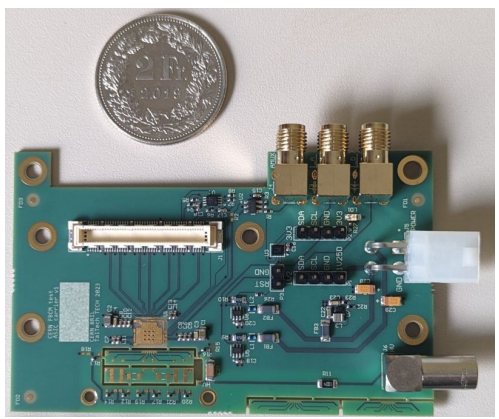
- Test and read-out of the system with a radioactive source
- Fresh and irradiated sensors will be tested

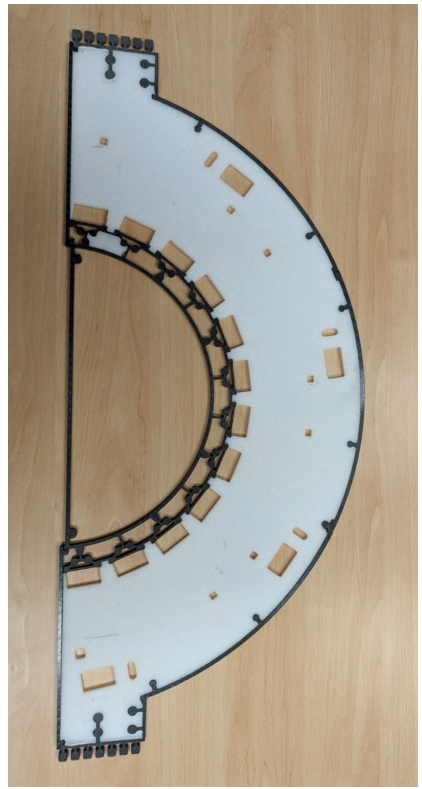
FC7 is a test and prototyping board used across CMS, hosts Kintex-7 FPGA with multi-gigabit transceivers and 2 FPGA mezzanine cards (FMC) slots.



Current status

- FBCM ASIC expected September 2023
- Test board and adapter mezzanines manufactured
- Half-disk mock-up available
- Thermal prototype
- DC-DC module customization finished
- Portcards being modified to add I2C master port
- Characterization and irradiation campaign for 6-pad sensors ongoing
- Mechanical design being optimized to improve thermal performance





Summary

- Dedicated stand-alone luminometer Fast Beam Condition Monitor (FBCM) is under development and prototyping
  - Fast binary front-end with dedicated ASIC and sensors
  - On track for Phase-2 upgrade (HL-LHC)
  - Instrumental for HL-LHC to achieve luminosity measurement with 2% uncertainty online and < 1% offline
- FBCM designed to be reliable and highly modular system
  - Avoids single point of failure
  - Designed for robustness and maintainability
  - Uses standard and tested HL-LHC radiation-hardened components: optical links, power supplies
- Testing and characterization of FBCM system starts soon
  - Electronic design of the front-end test system ready
  - Several stages for testing of ASIC, sensors, firmware
  - ASIC and sensor irradiation campaign is scheduled. Final decision on the choice of the sensor technology will be made based on the outcomes
  - System tests and validation with test beam