Isfahan University of Technology Cooperation in CMS Upgrade

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Isfahan university of Technology

Cooperation in BRIL Upgrade Program

- Isfahan University of Technology became full member of CMS in 2019.
- CMS members are expected to contribute to the Phase-II upgrade.
- IUT had meetings with different CMS groups and visited their laboratories to find the best project to cooperate in Phase II upgrade.
- Finally, IUT reached an agreement with the BRIL group to investigate and design an independent precision luminometer detector we called it “Fast Beam Condition Monitor” (FBCM)

BRIL Group

- The Beam Radiation, Instrumentation, and Luminosity (BRIL) group operates a number of detectors for measuring the luminosity and monitoring beam conditions and detector protection.
- LHC is sending billions of protons at each other per second. We need to measure how many of them actually are colliding. This measurement is called “luminosity”.
- Luminosity is an important input to nearly any measurement that will be performed on the resulting data.
- Luminosity is used also to optimize LHC operations.

Why FBCM?

- CMS Upgrade coordination endorsed R&D towards the development of a stand-alone luminosity monitor for CMS in Phase II,
- Providing redundant and complimentary luminosity measurements
- Fully independent frontend of the central Trigger and DAQ services
- Bunch by bunch online luminosity measurement for max. availability
- Plan for precise timing information
  - No system has asynchronous / sub-BX timing capabilities: understand time structure of the beams, beneficial for BIB measurement

FBCM functionality

- Luminosity measurement
  - Independent operation
  - Orthogonal systematics to other luminometers
  - Bunch-by-bunch (BX) measurement @40 MHz
  - Statistical uncertainty: << 1% per second for online measurement
  - Linear operation: < 0.02% Hz/μb

- Beam-induced background (BIB) measurement
  - Important for more accurate luminosity measurement
  - sub-BX timing
  - BIB time separation

Luminosity measurement

- Measurement Methods
  - Hit (or Cluster) counting
    - Used in HF project
  - Zero-counting method
    - Used in ATLAS BCM and Bril BCM1F luminometers

Hit counting increases the complexity compared to the zero-counting method.

We follow the Zero-counting approach.

- Suitable particle detectors
  - Depleted silicon sensor
  - Diamond sensor

Silicon vs Diamond sensors

- Depleted silicon
  - No erratic leakage current
  - More linear
  - Less radiation-hard
  - Needs cooling
  - ~ 67 to 87 pairs/μm
    - ⇒ ~25,000 e for 300μm
  - Charge collection time ~5.9 ns

- Diamond
  - Erratic leakage current
  - High hit rate affects adversely→ less linearity
  - Radiation-hard
  - Less cooling requirement
  - ~ 36 pairs /μm
    - ⇒ ~18,000 e for 500μm
  - Charge collection time ~2.5 ns

- BCM1F had a successful experience with silicon sensors in Run II
- For Run III, silicon sensors will be used as a baseline in BCM1F

- A silicon-based detector could be more linear and a stable luminometer

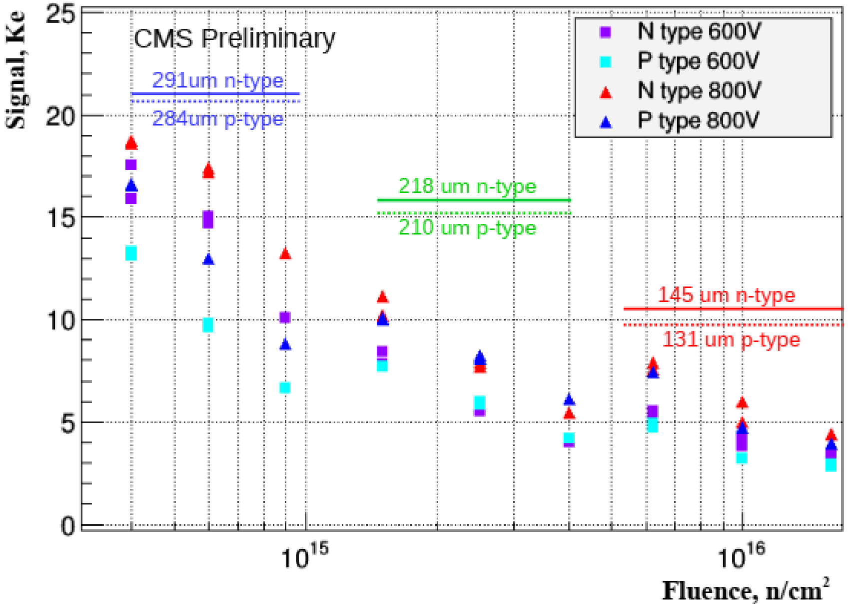
Silicon sensors will be used in FBCM.

Silicon sensors

- Silicon-sensors in FBCM follow the available technologies already developed for Phase-II CMS upgrade.

- AC-coupled sensors

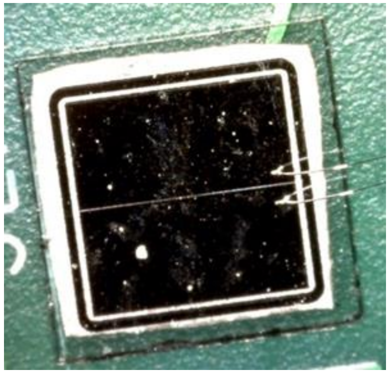
Charge collection efficiency for 300, 200 and 120 μm silicon sensors. Ref: https://cds.cern.ch/record/2020886

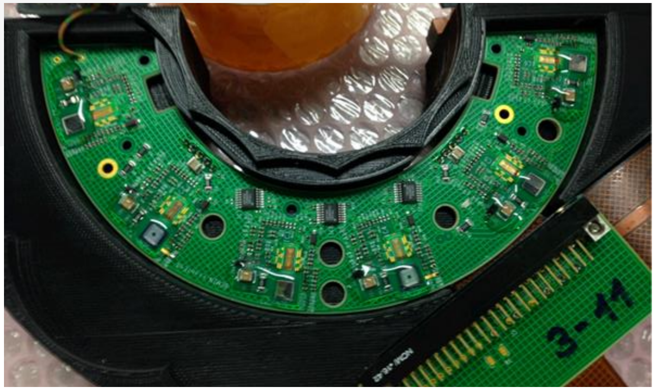


Available thicknesses	Capacitance (DC-coupled)	Unirradiated Deposited charge for a MIP @600V	Aged after 3000 fb^{-1} Deposited charge for a MIP @600V
300 μm	~38 pF/cm^2	~22 ke	~10 ke
200 μm	~55 pF/cm^2	~15 ke	~6 ke
120 μm	~96 pF/cm^2	~9 ke	~4 ke

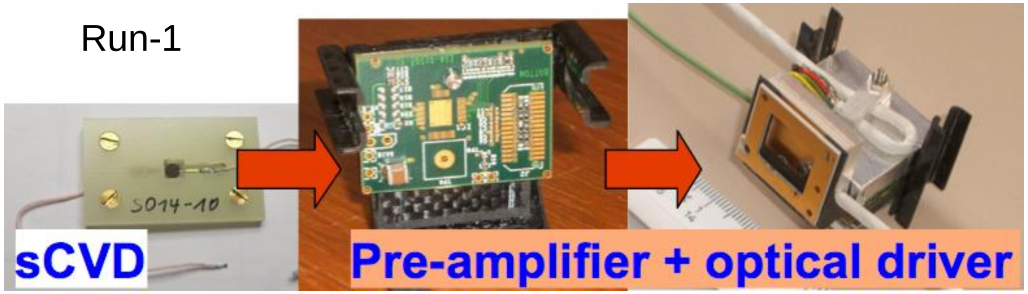
FBCM Electronics Challenges

- **High radiation in the trackers**
  - ✓ **Up to 10 MGy and 2 x 1016 n/cm2**
  - ✓ **Radiation hard IC technology**
- **High speed Links and chips**
- **Finding appropriate location to be installed**
- **Low power design and efficient power distribution**



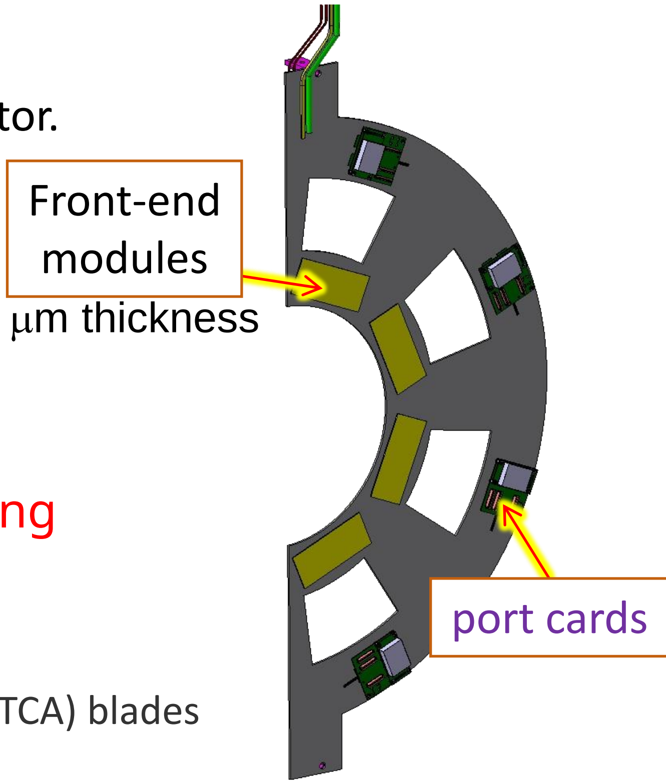


Run-1

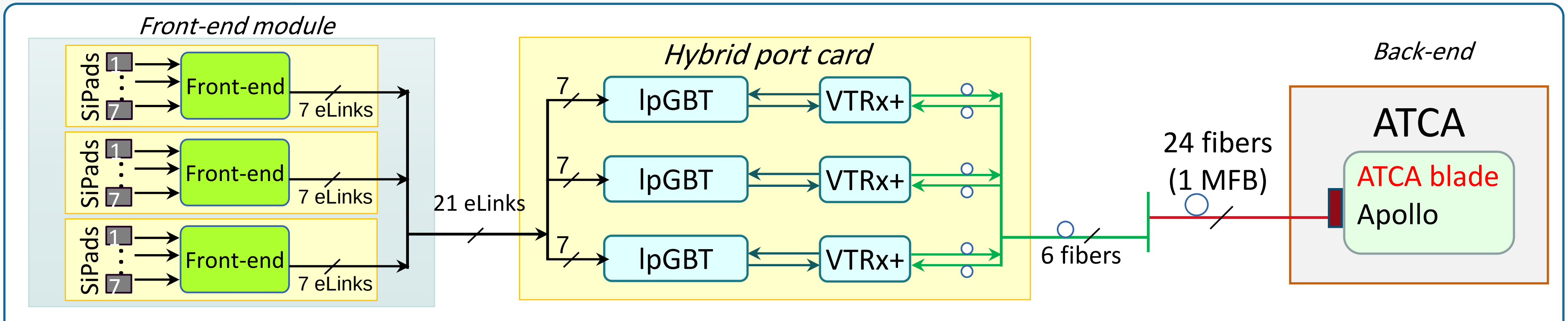


FBCM building blocks

A FBCM quarter
as an example of illustration



- The FBCM will be divided into four quarters
  - one quarter covers one half at one end of the detector.
- The key components:
  - Front-end modules (4 per quarter):
    - Sensors → 21 silicon-pads per module, 300 μm thickness
    - Front-end ASIC
  - Hybrid port cards (4 per quarter):
    - Opto-transmission + control and monitoring
      - lpGBT & VTRX+
- Back-end
  - Advanced Telecommunications Computing Architecture (ATCA) blades
- FBCM features 336 silicon-pad sensors

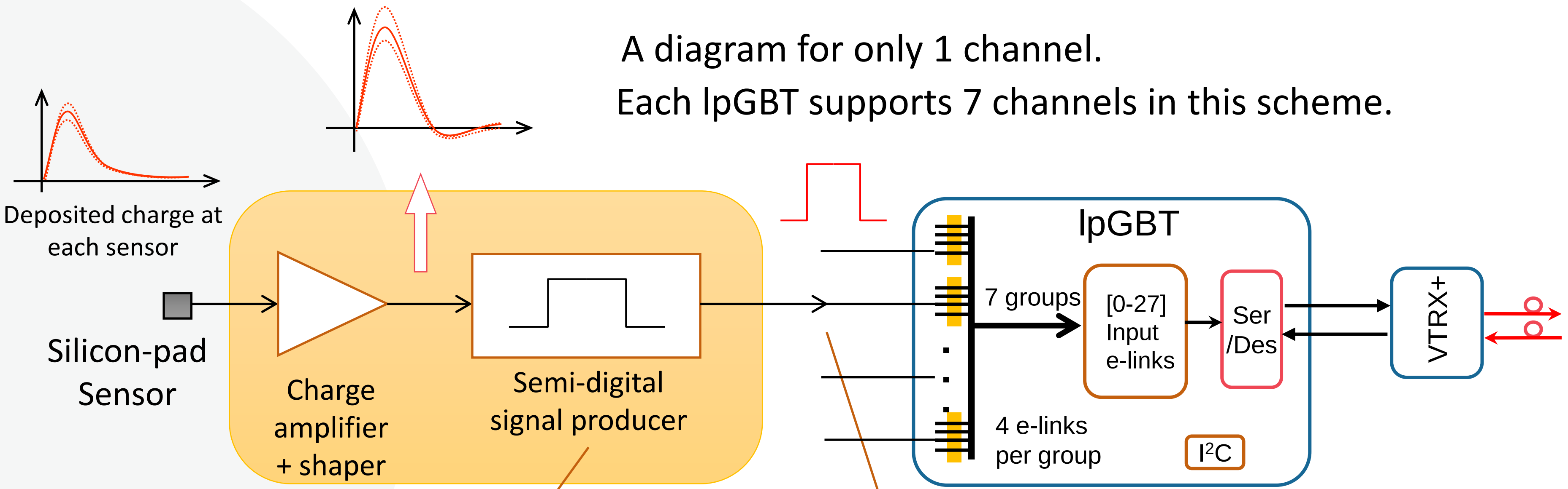


Architecture of a quarter of FBCM

Read-out chain and protocol

A diagram for only 1 channel.

Each lpGBT supports 7 channels in this scheme.



- Constant fraction discriminator (CFD)
- or fixed threshold discriminator

lpGBT continuously samples the semi-digital output @ 1.28 Gb/s

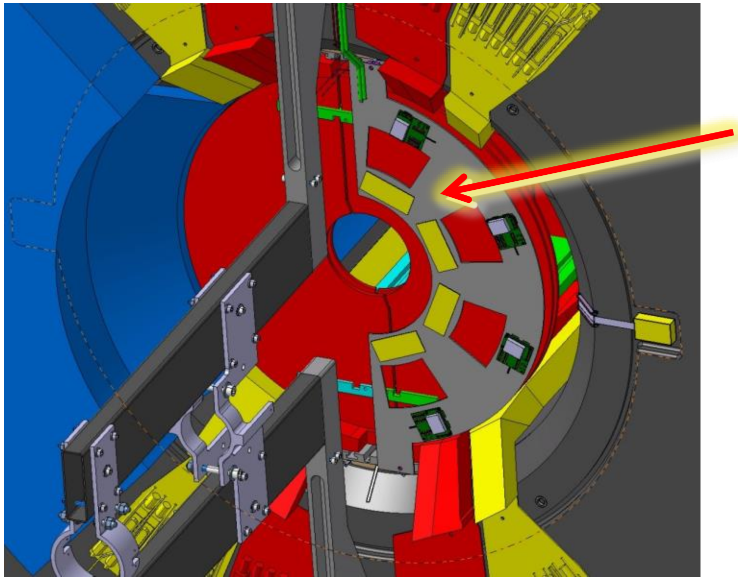
- Front-end ASIC:
  - A customized ASIC design,
- The ATCA processing unit histograms the number of hits per BX
  - Then the fraction of events with zero hits per BX is computed
  - The Zero-counting of hits

Location and environment

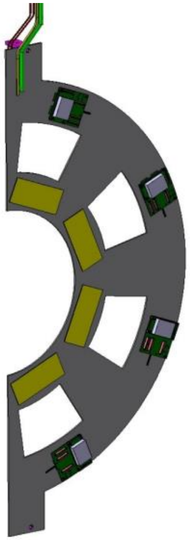
- At z= ± 283.5 cm
  there is a 14-cm space
- 8.5 cm < R < 21 cm, $|\eta| \sim 3.5$
- 84 sensors per quarter

- Radiation environment:
  - For R > 12 cm
    - ~3.5 hits/cm² per bunch-crossing

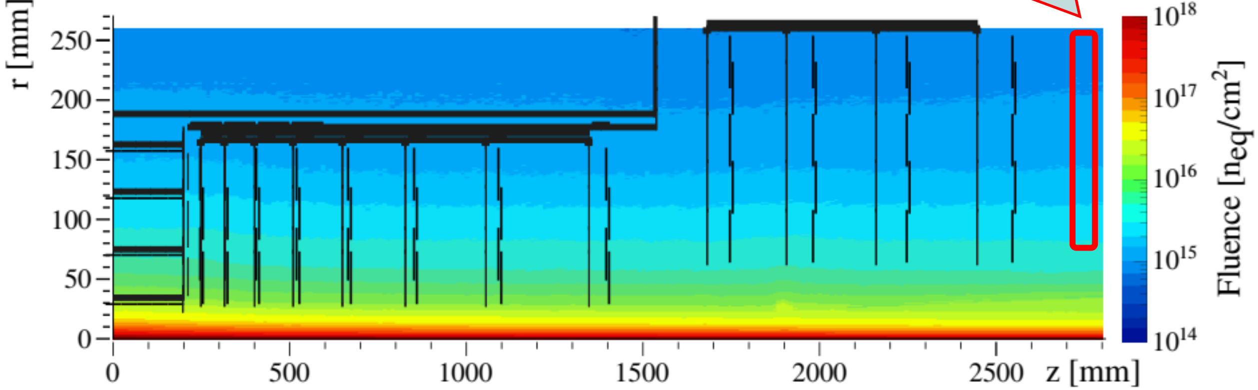
    @ 3000 fb⁻¹
    - TID < 200 Mrad
    - 1MeV neq fluence < 3.4x10¹⁵



A quarter of FBCM as an illustration



Anticipated Location



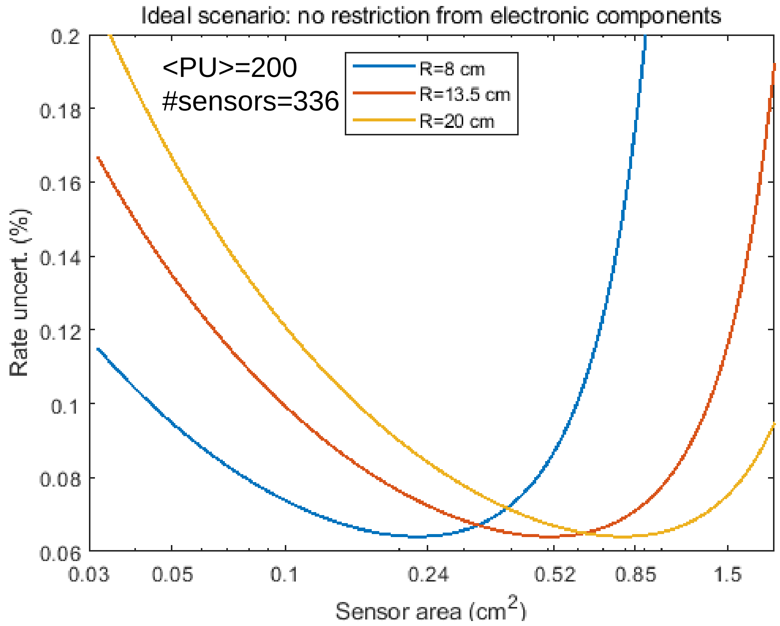
Integrated particle fluence in 1 MeV neutron equivalent in silicon per cm², with total integrated luminosity of 3000 fb⁻¹ of pp collisions at $\sqrt{s}$ = 14 TeV, using CMS FLUKA v3.7.2.0.
Ref: https://cds.cern.ch/record/2272264

Sensor size optimization
An ideal scenario

- If there were no restriction on the electronic components:
  - No limitation on the linearity would appear
  - $\Rightarrow$ Rate uncertainty becomes minimum at somehow large areas

Analytical estimation:

Sensor area of 0.52 cm^2 minimized the rate uncertainty at R=13.5 cm.

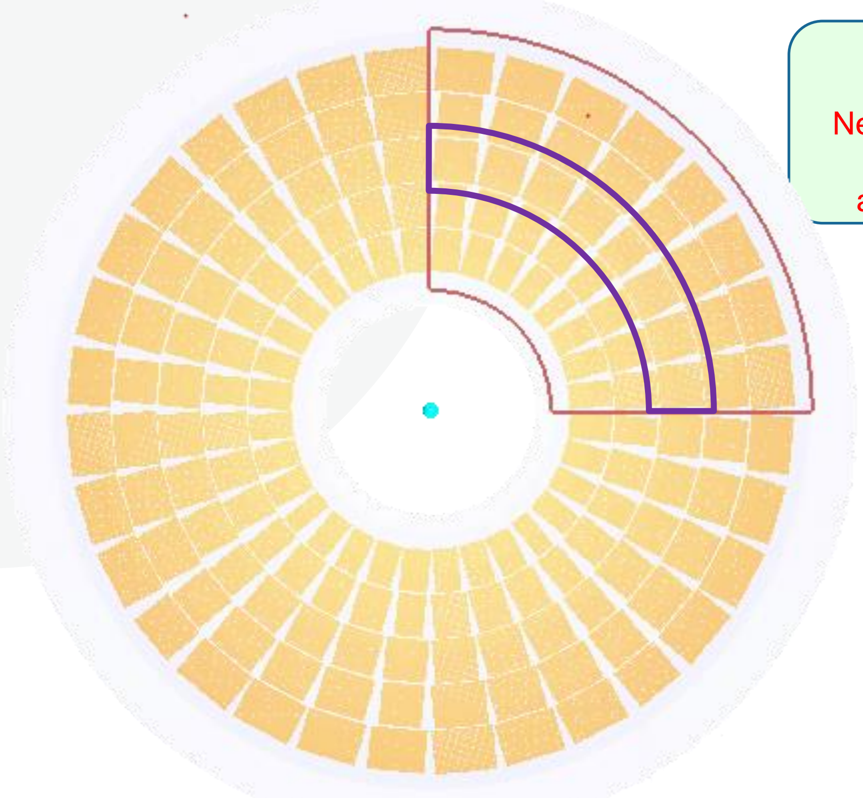


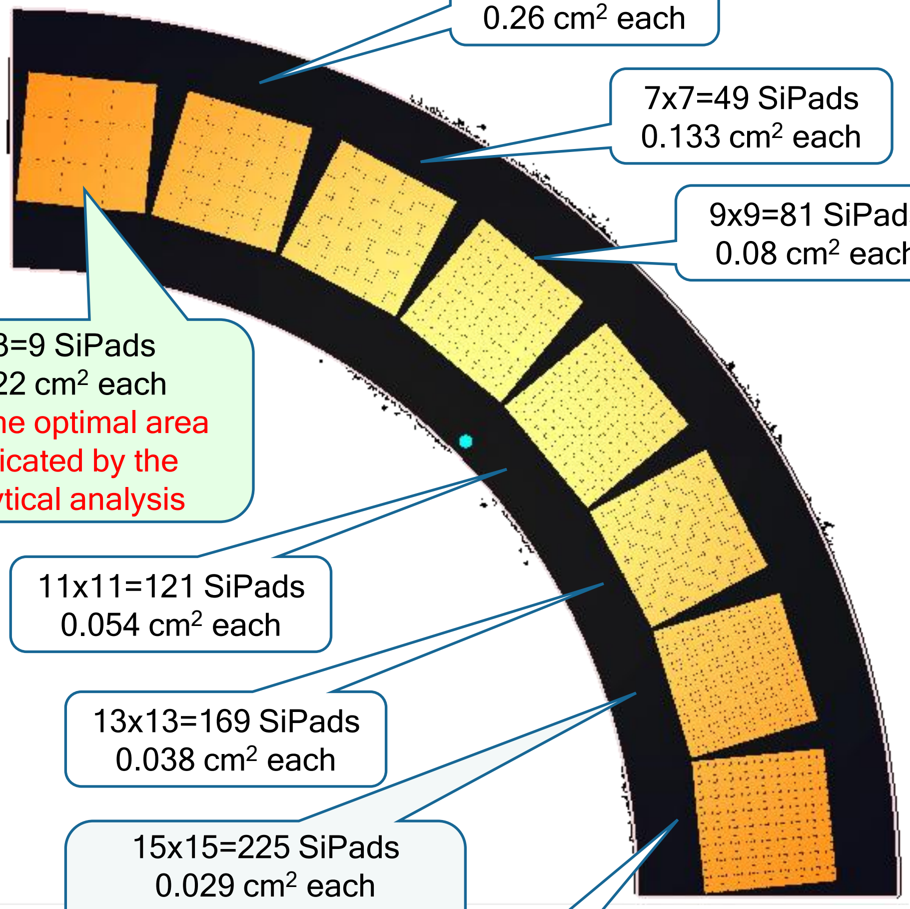
Ideal scenario: no restriction from electronic components

- However, the electronic elements (e.g. the front-end ASIC) will definitely degrade the performance.
  - Need smaller size of sensors as discussed in the following.

FBCM simulation & optimization

- 8 different size of sensors
- Placement radius spanning from 8 cm to 21 cm
- z=±283.5 cm
- GEANT4 – CMSSW simulation





5x5=5 SiPads
$0.26\ \text{cm}^2$ each

7x7=49 SiPads
$0.133\ \text{cm}^2$ each

9x9=81 SiPads
$0.08\ \text{cm}^2$ each

3x3=9 SiPads
$0.722\ \text{cm}^2$ each
Near the optimal area predicated by the analytical analysis

11x11=121 SiPads
$0.054\ \text{cm}^2$ each

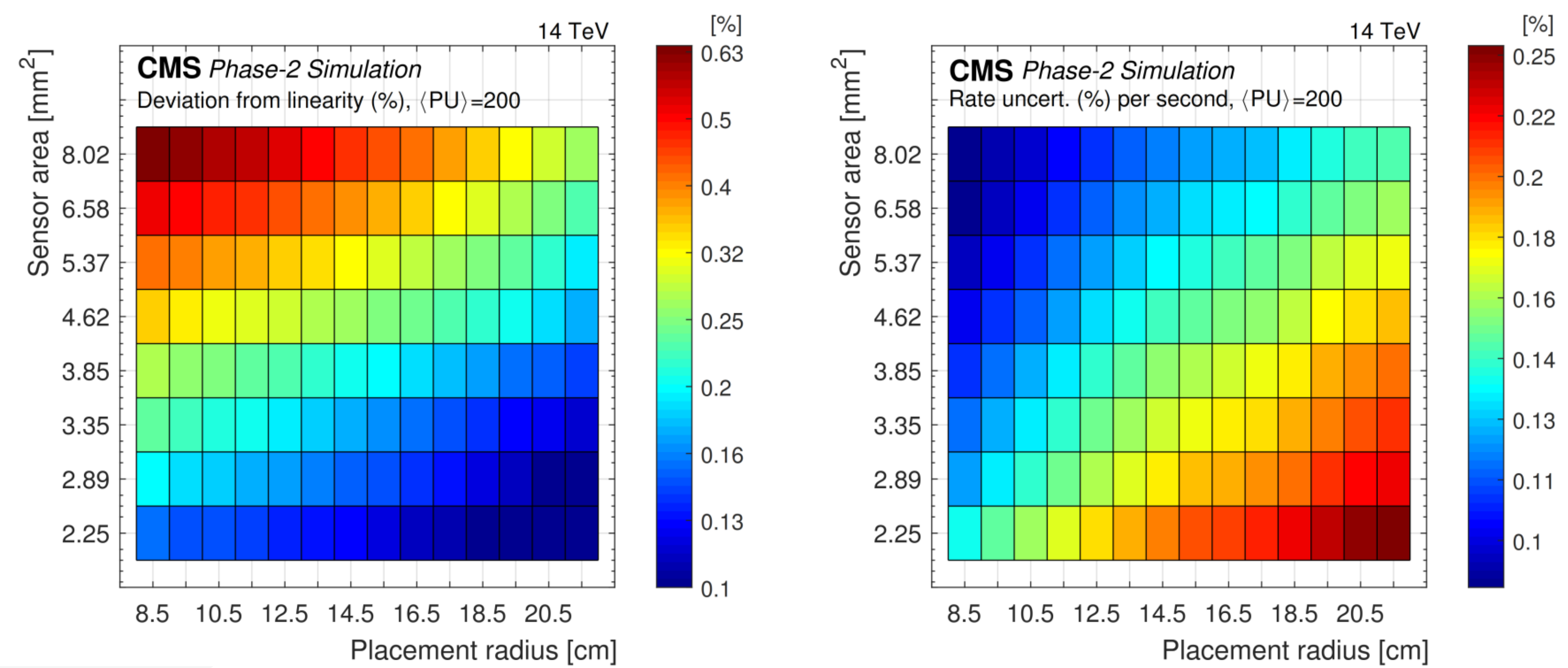
13x13=169 SiPads
$0.038\ \text{cm}^2$ each

15x15=225 SiPads
$0.029\ \text{cm}^2$ each
Exactly equal size to the BCM1F new sensors

17x17=289 SiPads
$0.022\ \text{cm}^2$ each

A hypothetical geometry only for simulation & optimization

FBCM expected performance: linearity vs rate statistical uncertainty



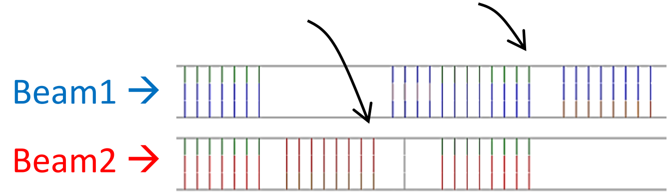
assuming 336 sensors

- Larger area sensors:
  - Worse linearity behavior, degraded statistical precision
- Small area sensors:
  - Good linearity behavior, increased statistical precision
- A trade-off between the linearity and stat. uncert.

Beam-induced background (BIB)

- Based on time separation of received particles in FBCM
  - At the beginning of a bunch train
  - At non-colliding bunches with enough free time before decaying albedo

Of interest of BIB:



- Timing definition and BIB signature:

z_d=283.5 cm

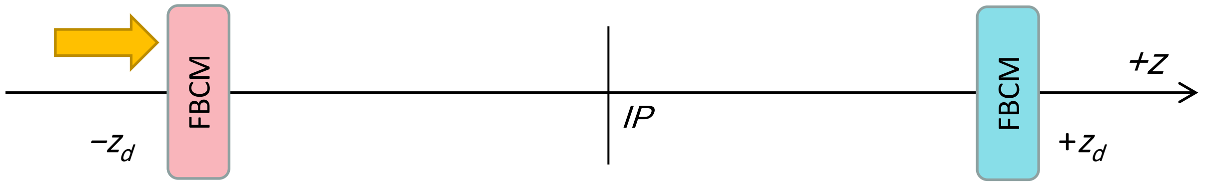
ToA = – 19 ns means
6 ns after previous BX

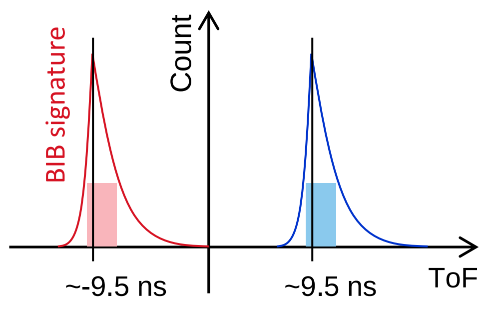
⇒ **ToA = 6 ns**

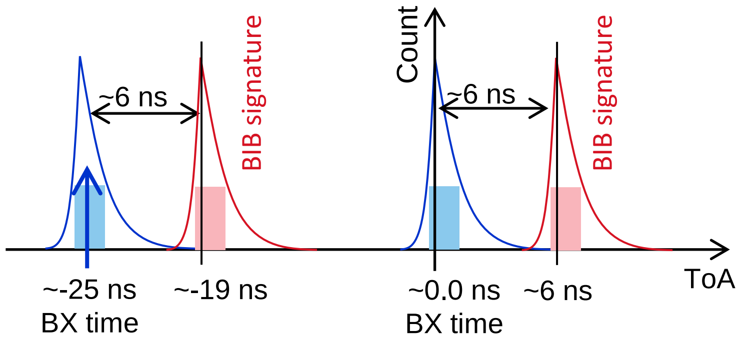
ToF = – 9.5 ns
ToA = ToF – 9.5 = – 19 ns

ToF = 0 ns
ToA = – 9.5 ns

ToF = 9.5 ns
ToA = 0 ns

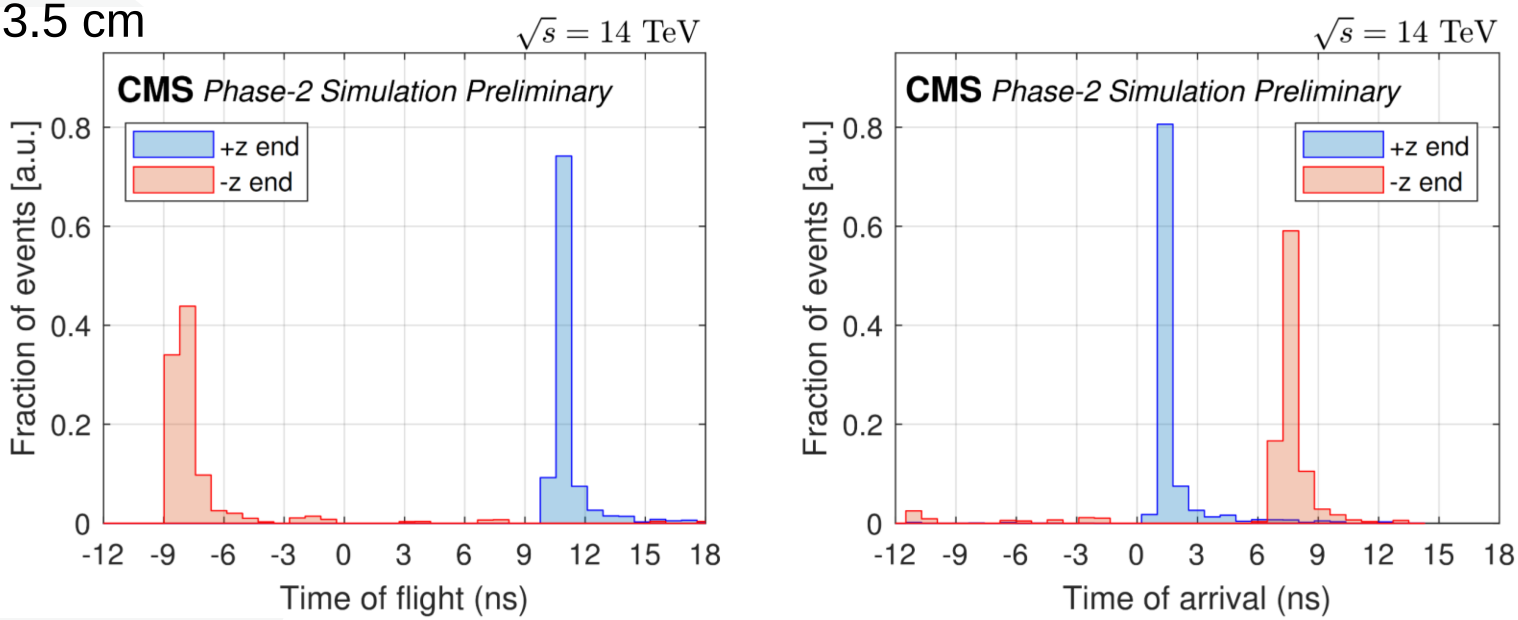






Beam-induced background

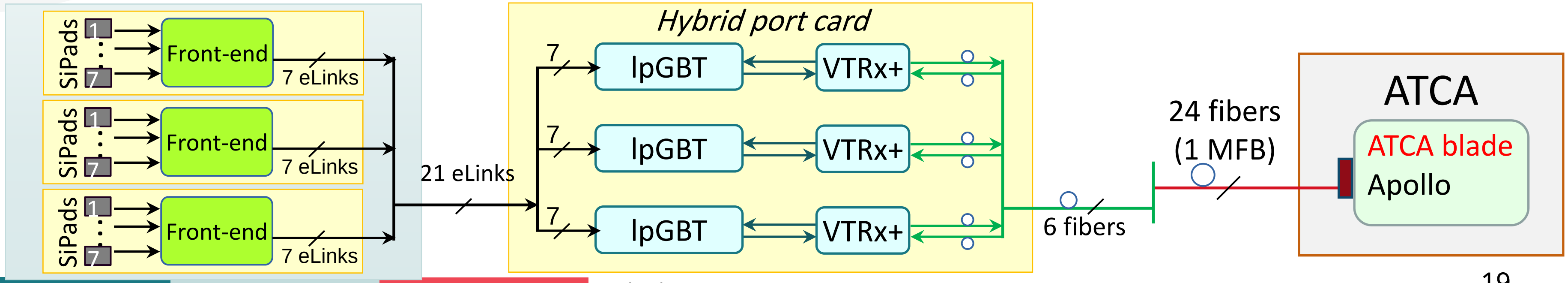
z=±283.5 cm



- The BIB simulations using CMSSW with input from FLUKA:
  - Beam-halo, i.e. interactions with LHC collimators
  - Interactions with residual gases (carbon, oxygen and hydrogen)
  - Assuming only one beam passing from -z to +z.
- Using a time binning of 0.78 ns it is possible to:
  - Recognize the incoming BIB received @ ToA=6 ns
    - in the beginning of a train
    - or with a non-colliding bunch after ~30 empty bunches

Future plan

- Technical Design Review is recently approved by LHC and is going to be published.
- IUT will cooperate with BRIL in detail design level of FBCM to prepare engineering design review (EDR).
- Detail design could be in one of the following tasks.
  - Detail design and testing of the Front-end ASIC
  - Detail design and testing of the Front-end module
  - Back end design and programing
- IUT is currently in talks with BRIL to finalize its future participation



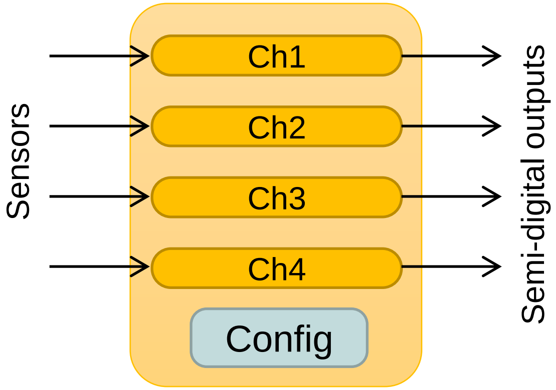
frontend ASIC detail design

Main Specification:

- Independent of Clock and CMS state operation
- Compatible with LpGBT or PicoTDC chips
- Multi-channel (>4chanel)
- Suitable input dynamic range for silicon sensors(~fC)
- High speed to have an acceptable rise and fall time (~ns)
- Providing TOA and TOT information
- Low electron charge noise (100s e)
- Radiation hard (~200MRad)
- Compatible with input capacitance (>2pF)
- Calibration circuit with configurable input charge
- Double hit resolution (25ns)
- TOT linear operation

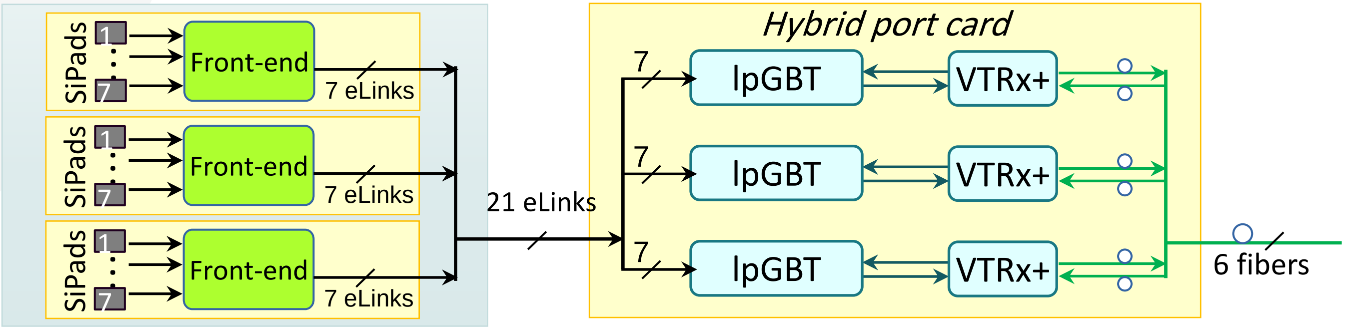
Timeline

- Start of 3 year development Q3 2021
- Prototype 1 Q2 2022 (analogue)
- Prototype 2 Q1 2023 (analogue + digital)
- Prototype 3 Q3 2023 (final)
- Pre-production Q2 2024



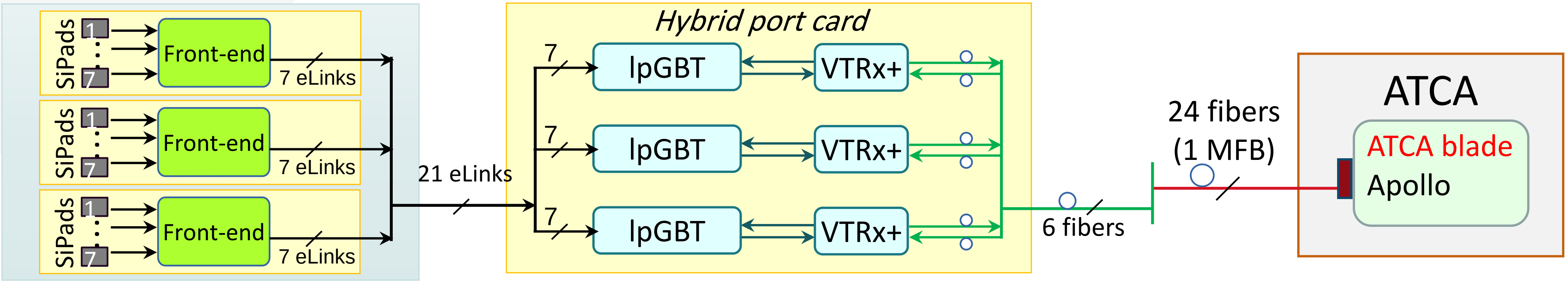
Frontend Module detail design

- Sensors Design and testing
- Prototype fabrication
- Prototype Testing and Optimization



Backend Design and programing

- ATCA programing for data preprocessing
- Design of a optimized protocol for real time luminosity measurement
- Implementation of protocols for real-time luminosity measurements



Summary

- The Fast Beam Conditions Monitor (FBCM), is the proposed stand-alone luminometer based on
  - 336 silicon-pad sensors & digital read-out with sub-BX resolution
- FBCM features:
  - Zero-counting for luminosity determination bunch-by-bunch,
  - Ability to transmit the ToA and ToT with a sub-ns resolution @40 MHz
  - Capability to measure beam-induced background (BIB).
- The expected performance of FBCM detector were simulated with CMSSW.
  - At pileup of 200 on average (336 sensors, each 2.89 mm^2, R=14.5 cm):
    - Satisfactory deviation from linearity
    - Rate stat. uncert. < 0.18%
- FBCM was reviewed in different levels and finally approved by LHC and TDR is going to be published.

Thank you