Upgraded CMS Fast Beam Condition Monitor for LHC Run 3 Online Luminosity and Beam-Induced Background Measurements

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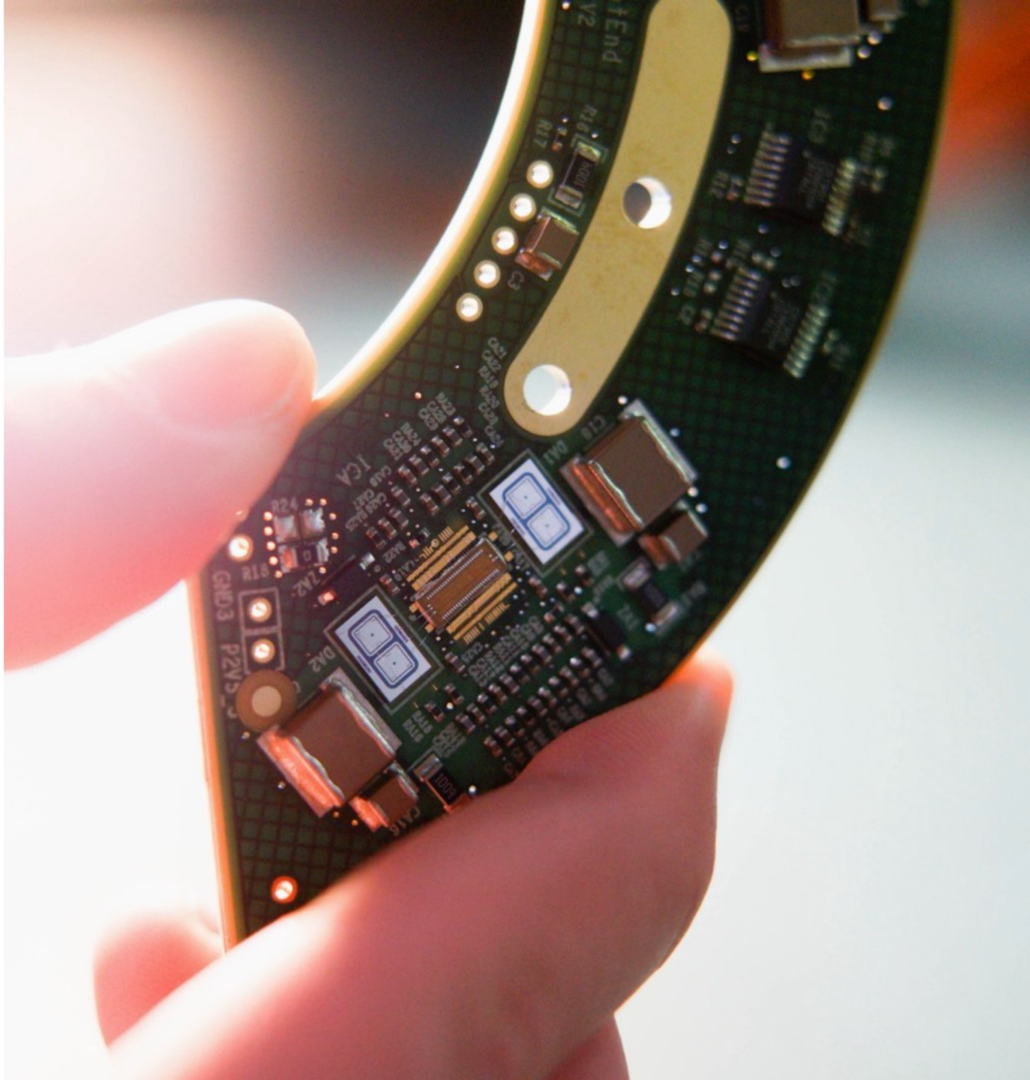
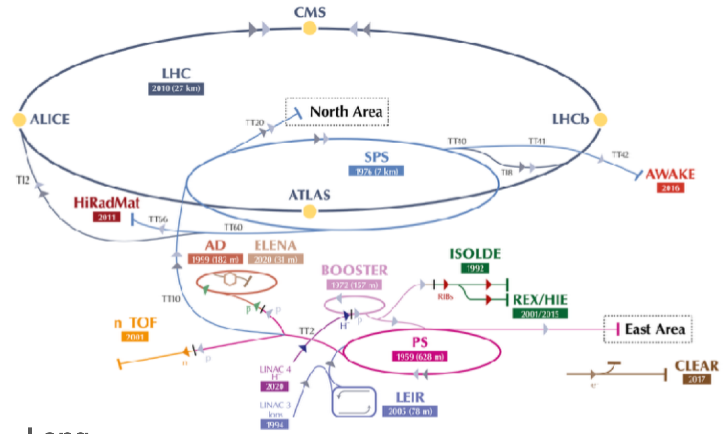


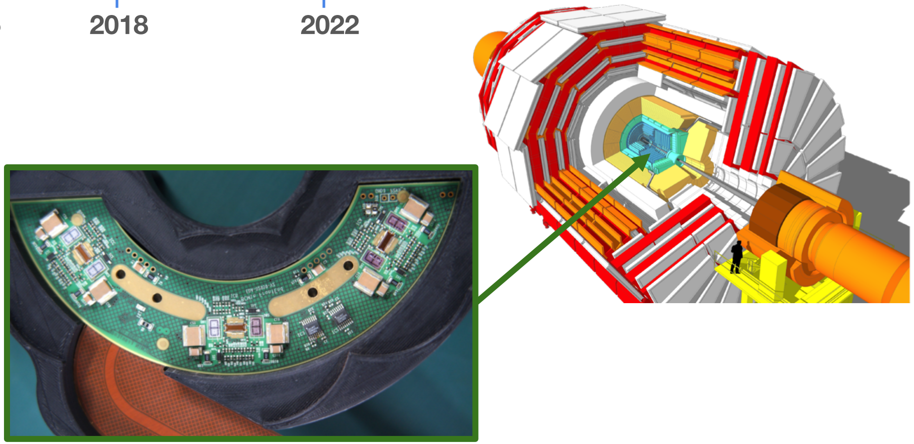
Introduction

➔ BCM1F is a part of the Beam Radiation Instrumentation and Luminosity (BRIL) Project at CMS
  - dedicated, standalone luminometer, independent from all central CMS services
  - sub-bunch crossing precision, enables the measurement of beam-induced background

➔ Good performance achieved in Run 2:
  - stable operation,
  - mixed sensor types were used: sCVD, pCVD and Silicon,
  - signal-noise separation and response linearity much better for the Silicon sensors

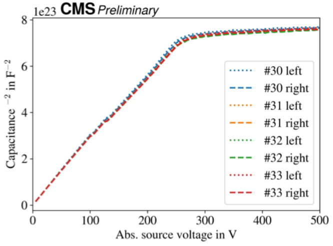
➔ Upgraded during LS 2 for precision luminosity in LHC Run 3:
  - new silicon diodes (CMS Phase 2 outer tracker PS silicon wafers), A/C-coupled
  - titanium circuit for active cooling (-20°C, C_6F_{14})

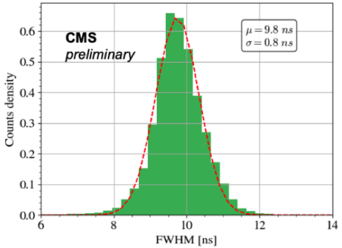




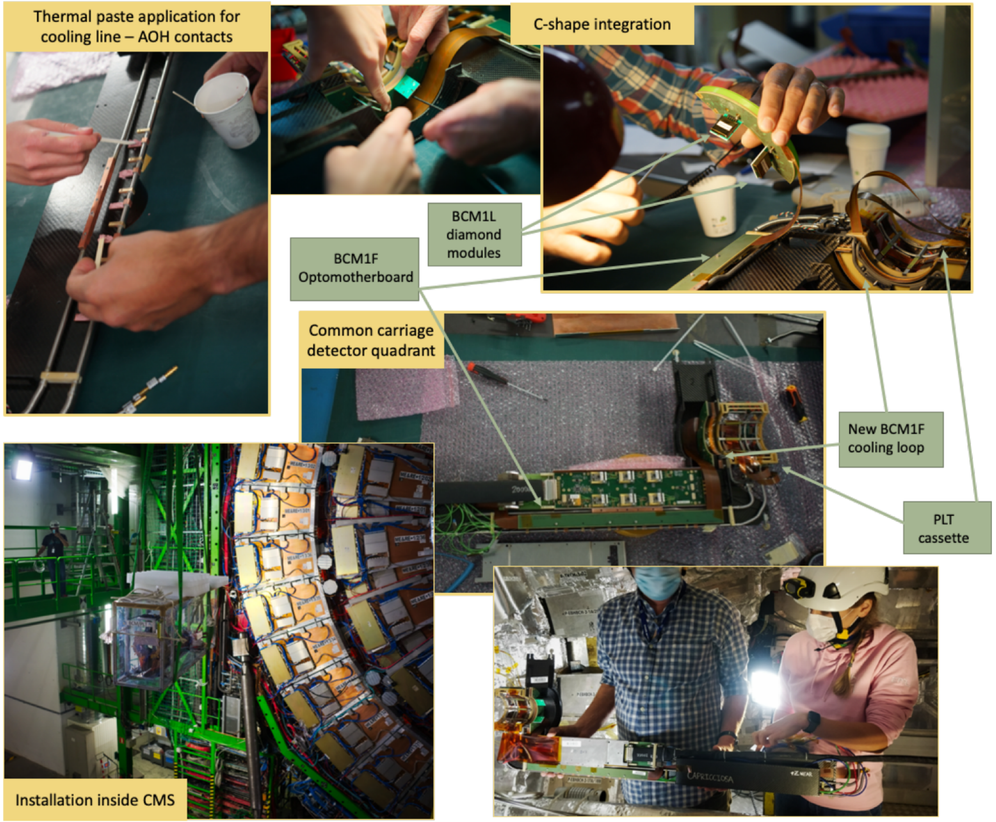
Detector assembly

- each C-shape pair forms a ring around the beam pipe at an approximate radius of 7 cm,
- total of 48 channels (4x12),





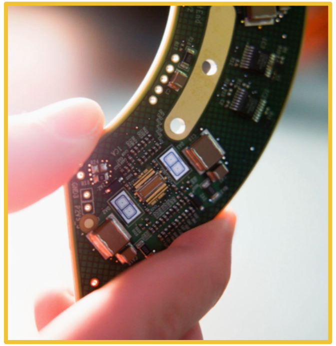
- integration with the Pixel Luminosity Telescope (PLT) and Beam Conditions Monitor for Losses (BCML1) on a common carbon fibre carriage,
- installation behind the CMS pixel detector, at a distance of 1.9 m from the IP (both sides).
- commissioning during the 2021 LHC pilot beam test at the injection energy of 450 GeV

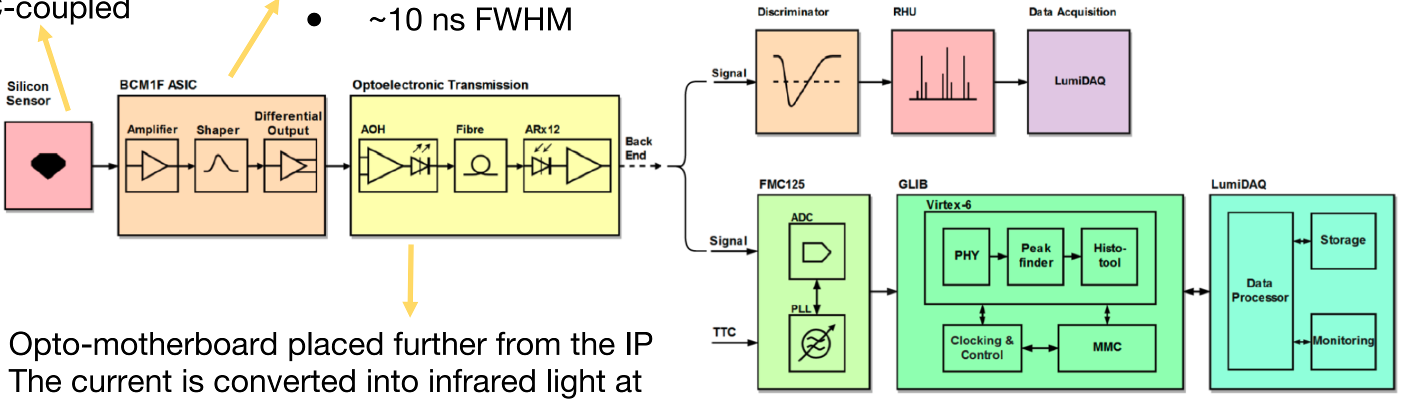


Detector description: front-end system

Sensors:
- 300 um thick
- 1.7×1.7 mm^2 area
- A/C-coupled

Amplifier:
- radiation-hard ASIC
- < 10 ns peaking time
- ~10 ns FWHM



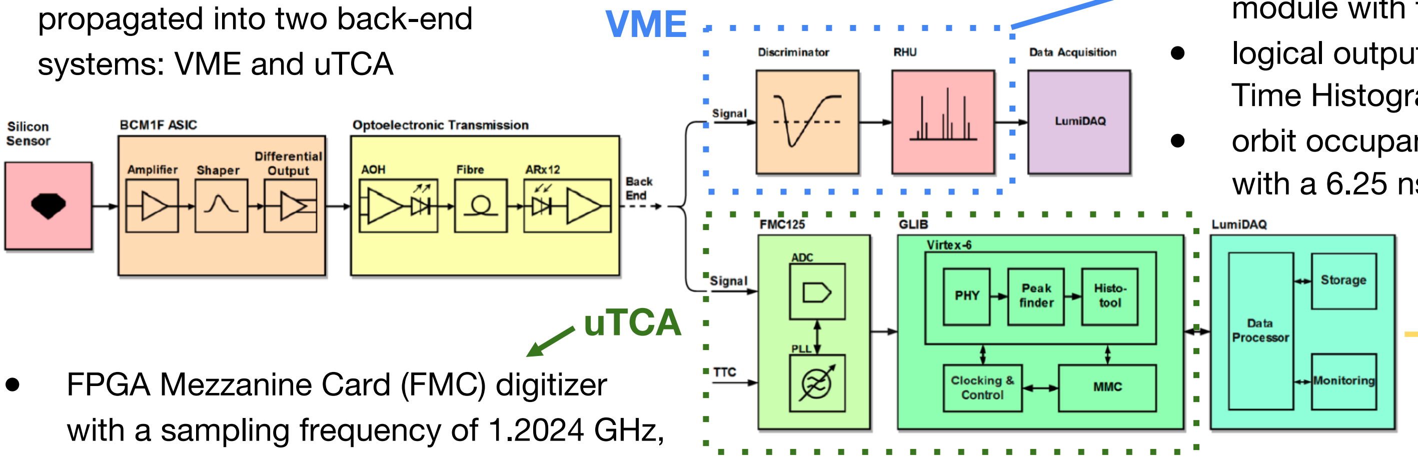


- Opto-motherboard placed further from the IP
- The current is converted into infrared light at a wavelength of 1310 nm

➔ The optical signal is converted into an analogue electric signal at the ARx12 optical receiver in the CMS service cavern (USC), shielded from the prompt radiation in the experimental cavern.

Detector description: back-end system

Signal is duplicated and propagated into two back-end systems: VME and uTCA



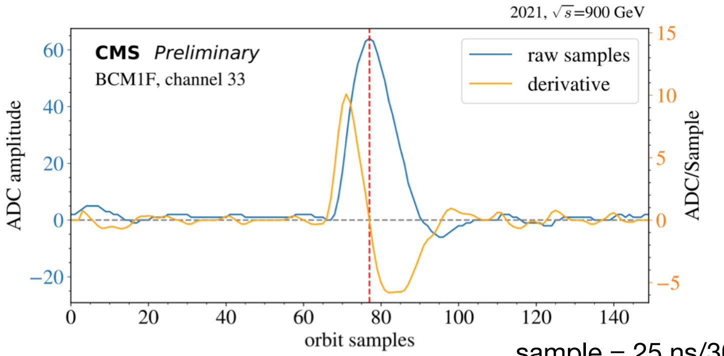
- a leading edge discriminator CAEN module with fixed threshold
- logical output is connected to the Real-Time Histogramming Unit (RHU) [9]
- orbit occupancy histogram is formed with a 6.25 ns granularity (4 bins/BX)

dedicated BRIL DAQ software, independent of the central CMS DAQ

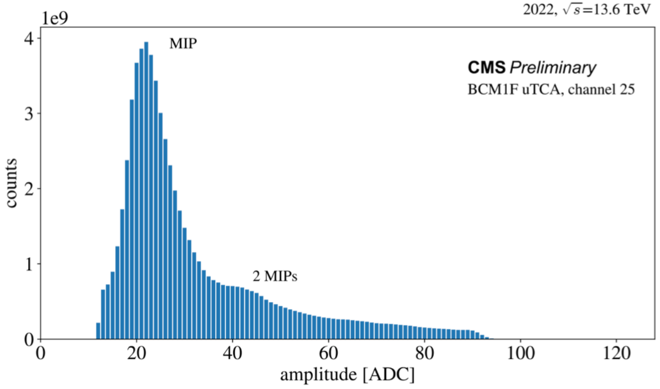
- FPGA Mezzanine Card (FMC) digitizer with a sampling frequency of 1.2024 GHz, A/C coupling of ADC inputs, and PLL to lock on the LHC bunch clock.
- peak finding and histogramming is performed on the Xilinx Virtex-6 FPGA hosted by the Gigabit Link Interface Board (GLIB)
- orbit occupancy histogram based on the arrival time, with enhanced resolution of 6 bins/BX
- derivative-based peak finder algorithm: multiple hits resolution and improved efficiency.

New Peak Finder

- ➔ new peak finding algorithm uses a derivative based threshold, which is designed to differentiate the overlapping pulses to maintain the detection efficiency at high pileup:
  - derivative calculated with a smooth noise-robust differentiator (SNRD, N=7): $\frac{5(f_1-f_{-1})+4(f_2-f_{-2})+f_3-f_{-3}}{32h}$
  - peak detection based on the derivative threshold level crossing,
  - designed to provide noise suppression at high frequencies with efficient implementation into a digital system,
  - electronics noise separated based on the low value of the maximum derivative, and by applying the amplitude cut off.
- ➔ The amplitude spectrum built with the new peak finder is a Landau distribution with the most probable value corresponding to the energy loss of the minimum-ionizing particle. The low amplitude Gaussian noise contribution removed with operational thresholds.



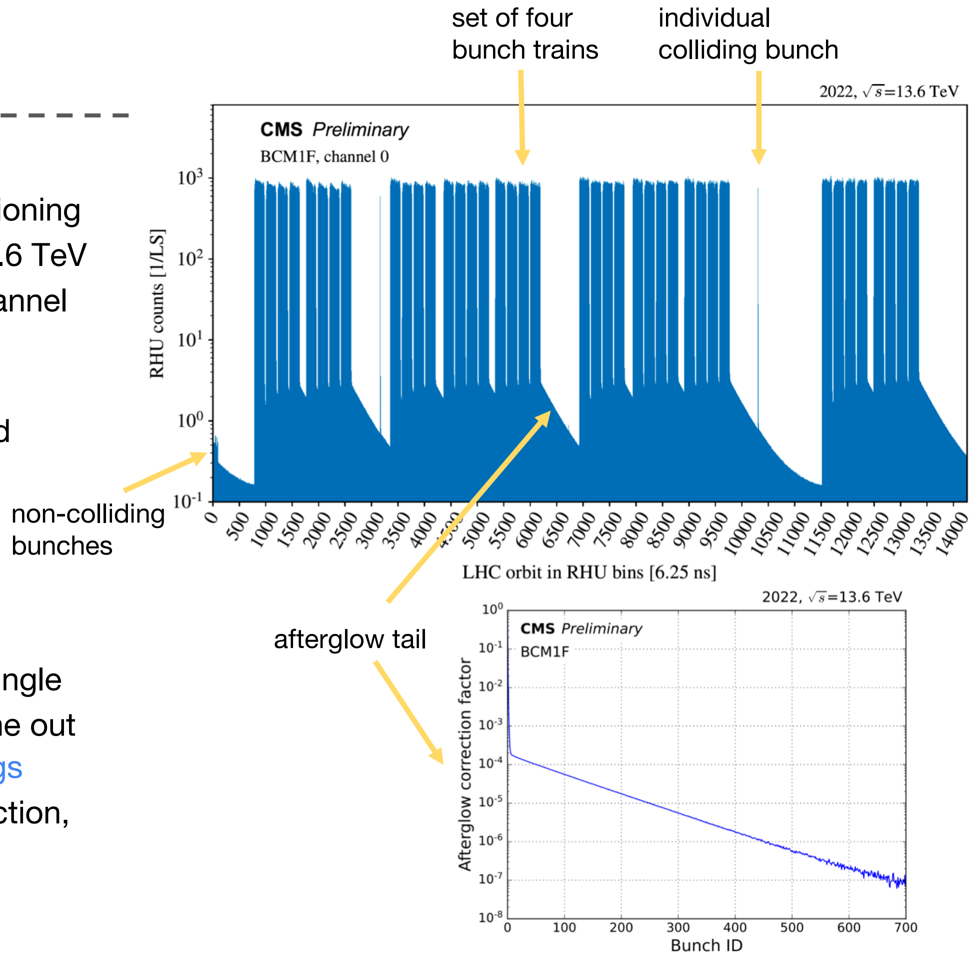
sample = 25 ns/30



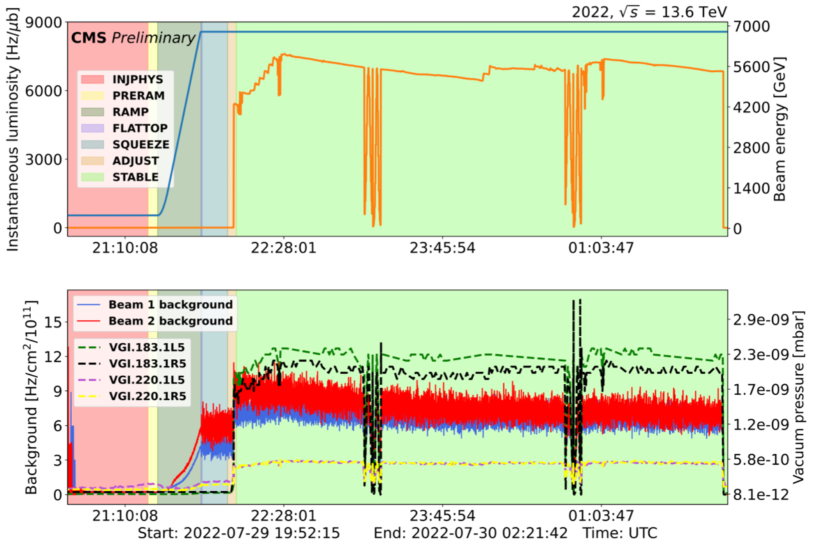
Run 3 commissioning

- ➔ operational since the beginning of LHC commissioning for the Run 3, including first measurements at 13.6 TeV
- ➔ detector configuration optimized with the per-channel timing alignment.

- ➔ additional hit count observed due to the activated detector material
  - ◆ signal contamination is corrected by applying an afterglow correction factor to each colliding bunch
  - ◆ signal from the two well-separated (~us) single colliding bunches is used to account for the out of time hits in the following bunch crossings
  - ◆ raw data were fitted to an exponential function, aggregated over many orbits.

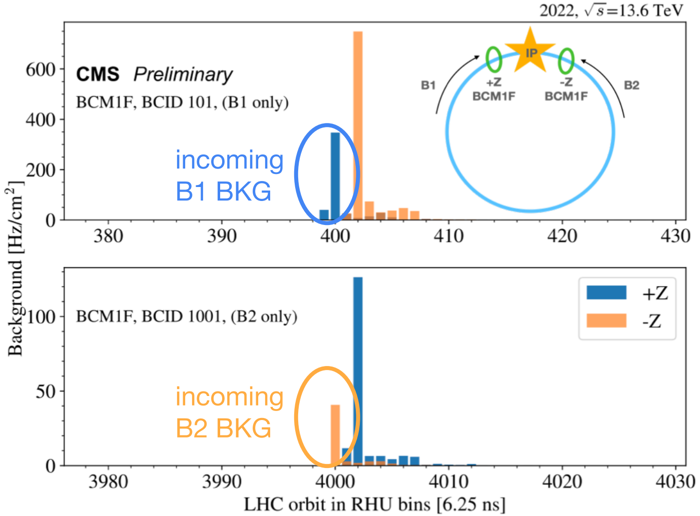


Beam-Induced Background Measurement



- Based on the BCM1F background measurements are used to assess beam conditions → guarantee safe operation for the other CMS subsystems
- real-time feedback of the beam conditions prevalent close to the CMS experiment to the LHC

- BIB particles are measured by different BCM1F channels, based on their location with respect to the CMS IP



- The beam direction can be resolved by the time of arrival: beam 1 signal is visible in BCID 101 before beam 2, and the opposite for the second presented BCID (circulating beams).

Luminosity Measurement - calibration

➔ BCM1F has been the main online luminometer since the beginning of the LHC commissioning period for Run 3,

➔ luminosity measurement is based on the sum of counts within a colliding BCID,

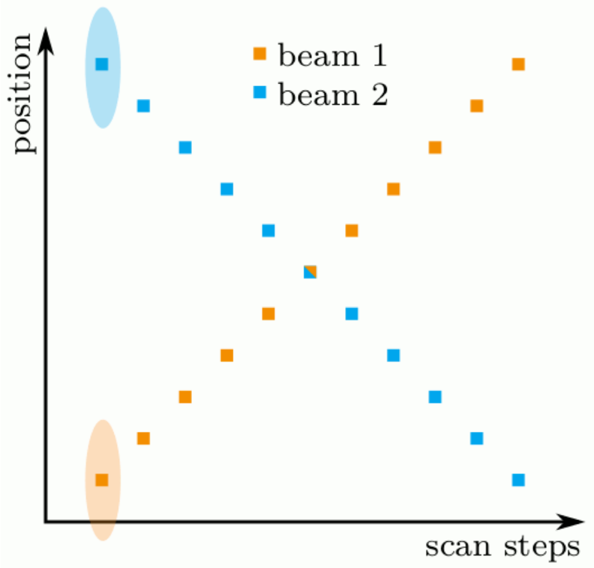
➔ zero counting algorithm is used:

$$\mu = -ln\left[p(0)\right] = -ln\left[1 - p(n \neq 0)\right] = -ln\left[1 - \frac{N_{hit}}{N_{bc}}\right]$$

➔ During van der Meer (vdM) calibration the visible cross section can be defined from measured rate:

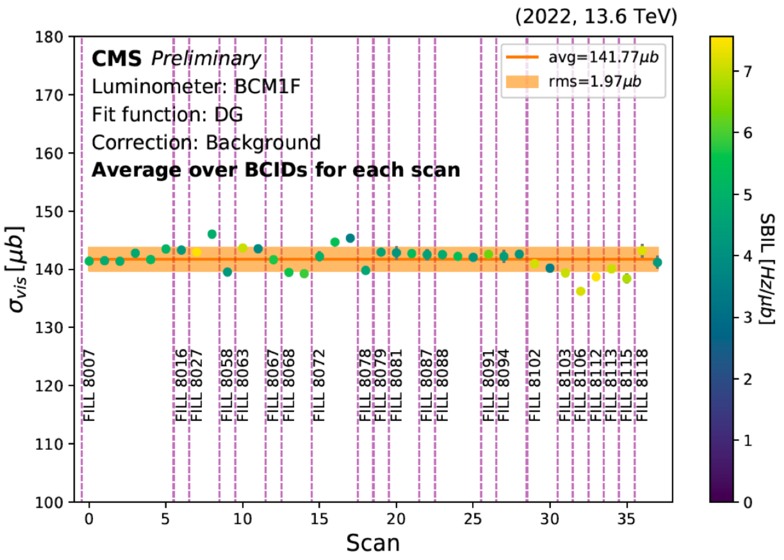
$$L_{inst} = \frac{N_1 N_2 f}{2\pi \Sigma_x \Sigma_y} \longrightarrow \sigma_{vis} = \frac{R}{L_{inst}}$$

➔ As the main vdM program is planned only for the end of 2022, emittance scans are used to obtain preliminary detector calibration.



Luminosity Measurement

- ➔ The stability of the online measurement can be observed with the calibration constant remeasured in subsequent scans.
- ➔ The BCM1F VME measurement in the early Run 3 period at nominal conditions shows a very good stability with 1.4% RMS on the visible cross section.
- ➔ For BCM1F uTCA each sensor is treated independently and a per channel calibration constant is extracted,
- ➔ the spread between fully optimized channels is within 15% from the average.



Beam Overlap Measurements

- separation scans are also used to study the bunch profile
- in the nominal conditions, crossing angle is used in x-z plane to avoid long-range interactions, hence the beam overlap includes its effect:

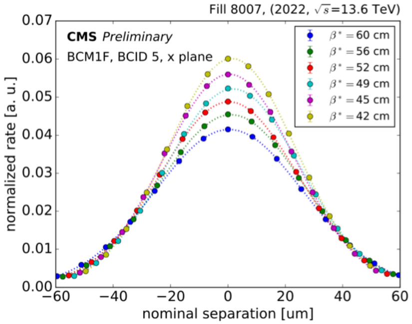
$$\Sigma_x = \sqrt{(\sigma_{x1}^2 + \sigma_{x2}^2)\cos^2\frac{\phi}{2} + (\sigma_{z1}^2 + \sigma_{z2}^2)\sin^2\frac{\phi}{2}}, \quad \Sigma_y = \sqrt{\sigma_{y1}^2 + \sigma_{y2}^2}$$

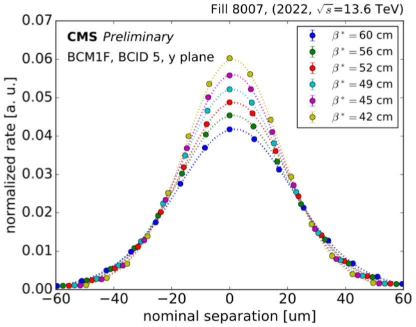
- Run 3 operation includes β* luminosity levelling - the overlap width decreases along these steps, as the beam size decreases with β*.

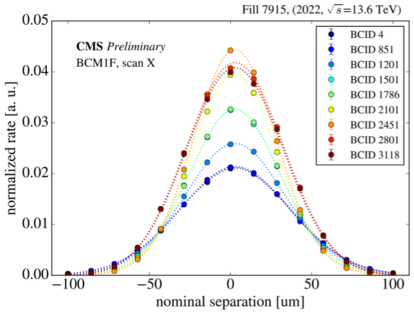
- The normalized emittance can be estimated after extracting the convoluted width of the two colliding bunches:

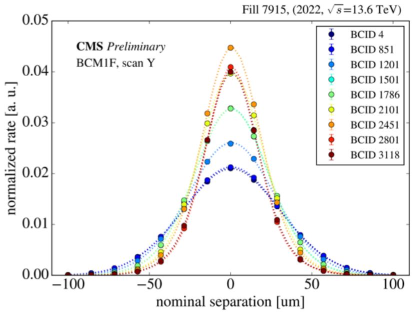
$$\sigma_{eff} = \sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}} \quad \rightarrow \quad \epsilon = \frac{\sigma_{eff}^2}{\beta^*}\gamma\beta_{rel}$$

- An example measurement was performed for a special fill which included bunches with wide range of normalized emittances: 3.95-7.25 um in x and 1.79-5.59 um in y.



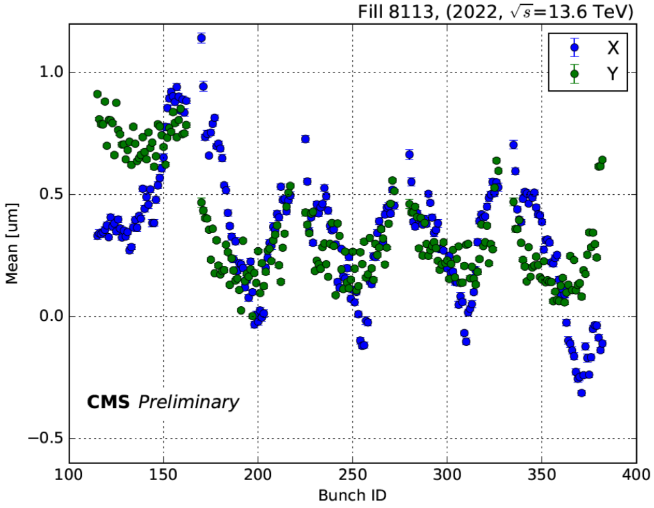






Orbit Displacement Measurement

- the mean value is extracted from a Gaussian fit to the normalized rate over separation steps,
- it indicates the per-bunch orbit displacement, with respect to the closed orbit, optimized before a scan.
- the displacements are dependent on the number of parasitic collisions per bunch for a given filling pattern,
- bunch train structures are observed by BCM1F in both transverse planes.
- This measurement is used for the improvement of systematic effects related to the beam-dynamics,
- it has already been used to benchmark the Beam-Beam effect simulations which are applied for the offline luminosity measurement.



Conclusions

➔ The commissioning of the upgraded BCM1F has been finalized,
➔ in the first months of the LHC Run 3, it has proven to be robust and reliable.

➔ It has continuously provided CMS and LHC with:

- online beam-induced background,
- and luminosity measurements,
- regular emittance scans enable an independent and non-destructive transverse profile measurement,
- and per-bunch orbit displacements.

➔ To achieve the best precision in luminosity measurement:

- per-channel BCM1F performance has to be investigated.
- dedicated vdM calibration is necessary, planned at the end of 2022,
- systematic effects have to be considered.

Thank you for you attention!

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