Test beam data analysis for validation of the front-end modules of the Phase 2 luminometer (FBCM)

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Abstract: For High Lumi LHC in the CMS experiment the standalone luminometer Fast Beam Condition Monitor (FBCM) is being designed. It is a silicon pad-based detector with dedicated fast ASIC. The High Luminosity LHC (HL-LHC) Phase 2 upgrade demands unprecedented radiation hardness and reliability from all detector subsystems.

In 2025, an extensive test beam data-taking campaign was successfully executed to collect operational data from the FBCM front-end boards. The tested modules include sensors at three distinct lifecycle stages: non-irradiated ("fresh") control samples, sensors irradiated to a half of the Phase 2 total integrated dose at the detector location (half-dose), and sensors that received the full Phase 2 dose (full-dose).

While the experimental planning assumes a scheduled replacement of the FBCM during technical stop after half of Phase 2 (corresponding to the half-dose threshold), unforeseen delays in the accelerator schedule could postpone technical maintenance. Therefore, it is critical to precisely model and understand the non-linear degradation, charge collection efficiency, and overall signal trustworthiness of heavily irradiated equipment beyond the half-dose limit.

Project description and deliverables. During the preparation for the beam test, the 6-pad sensors were irradiated at CERN IRRAD facility. As proton beam used for irradiation has a spatial Gaussian profile the central pads accumulated a significantly higher radiation dose compared to the outer peripheral pads. This non-uniform distribution provides an opportunity to study multiple irradiation levels on a single board by directly comparing outer and central channels.

The primary objectives of the data analysis include mapping the event detection rate as a function of the ASIC operational threshold (TH). The data analysis pipeline will be structured around the following key validation plots:

- **Time-over-Threshold (ToT) study:**

1. ToT histograms from all channels at fixed RC (resistor-capacitor) filter settings and fixed thresholds. This is useful for identifying channel-to-channel variations in heavily irradiated boards.
2. Detailed study of ToT vs. spill number to develop the filter to cut corrupted data

- **ASIC settings Parameter Space Exploration:** Systematic comparison of ToT distributions across different thresholds and RC-filter settings configurations.
- **ASIC threshold (TH) Scans:**
    1. Individual per-channel threshold distributions.
    2. Overlays of all RC settings for a given channel to find optimal settings for operation with fresh and irradiated sensors
    3. Overlays of all 6 channels under fixed RC settings to monitor spatial damage profiles.
- **Internal Efficiency Normalization:** Conducting full threshold scans where the 100% efficiency baseline is anchored to the first stable data point right after the noise floor cutoff, selected from the least irradiated (outer) pad on the board.
- **External Reference Integration:** Extracting tracking data from the CROC beam telescope to act as an external geometric reference, allowing absolute efficiency normalization of the FBCM efficiency profiles.

Work plan:

- **Weeks 1–3.** Understand the data processing framework. Designing automated data-quality monitoring (DQM) routines to identify noisy channels, or incorrect run configurations. This can be directly used at the upcoming 2026 beam test.
- **Weeks 4–6.** ToT histograms study for the range of RC/TH parameters for the fresh and irradiated boards.
- **Weeks 7–9.** Detailed comparative analysis of central vs. outer pads, relative efficiency study. Study of the correlation with external trigger data from CMS pixel module (CROC).
- **Weeks 10–12.** Documentation of the framework, adaptation of the scripts for 2026 data analyses.