Detector Performance and Upgrade Plans of the Pixel Luminosity Telescope for Online per-Bunch Luminosity Measurement at CMS

CERN Detector Seminar

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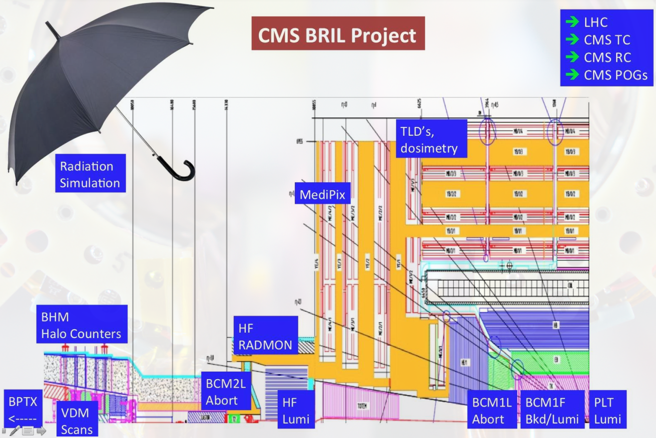
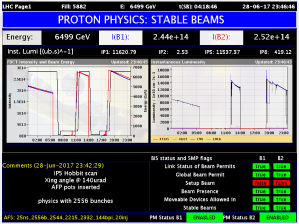
CMS BRIL Project

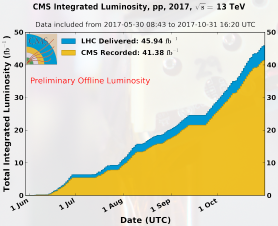
- BRIL = Beam Radiation, Instrumentation, and Luminosity
  - Oversees luminosity measurements, beam condition monitoring, radiation monitoring and simulation, etc.



LUMINOSITY MEASUREMENT

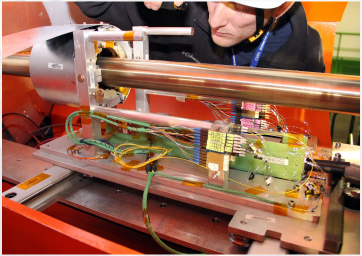
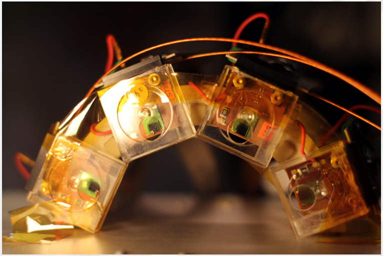
- Instantaneous Luminosity ($\mathcal{L}$) is a measure of the rate of "useful" collisions
  - Quantifies the ability of a particle accelerator to produce a certain number of interactions
  - Proportionality factor between the rate of interactions (R) and the cross-section of a particular process (σ): $R = \mathcal{L} \cdot \sigma$
- CMS luminosity measurement
  - Provides real-time monitoring the LHC's performance on a bunch-by-bunch basis
  - Provides overall normalization (integrated luminosity) for physics analyses





sCVD PLT History

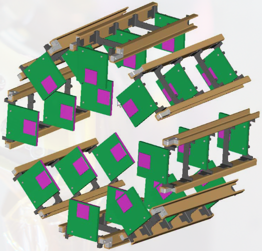
- Originally designed with single-crystal diamond sensors
  - Expected sCVD to be radiation hard without cooling requirements
  - Reduced efficiency at high lumi and with accumulated dose during 2012 pilot run and subsequent testbeams

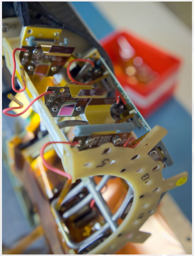



Left: Feb 2012 installation of sCVD PLT in the HF CASTOR Table. Right: Nov 2012 testbeam at PSI

PIXEL LUMINOSITY TELESCOPE

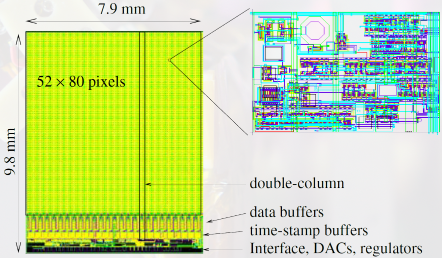
- Silicon pixel detector dedicated to luminosity measurement at CMS
    - Installed in 2015 before LHC Run 2
- Located 1.75m from the IP at both ends of CMS ($|\eta| \approx 4.2$)
- Arranged into 16 "telescopes" (8 per end)
    - Each telescope composed of three individual sensor planes
    - Same sensors and readout chips as phase-zero CMS pixel detector
- Online lumi: "triple coincidence" rate read out at 40MHz
- Offline lumi: full pixel information read out at $\sim$ 3kHz

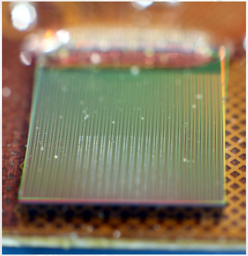




PSI46v2 Readout Chip (ROC)

- Silicon sensors with pixel pitch of 150μm in the column direction and 100μm in the row direction
- PSI46v2 ROC records hit position and amount of charge deposited in the silicon sensor with time resolution of 25ns
  - Charges collected from the sensor are suppressesed if signal is smaller than a programmed threshold
    - ROC threshold can be set globally and adjusted ("trimmed") for each individual pixel
  - Active area is an array of 52 $\times$ 80 pixel unit cells
    - Arranged in 26 double columns of 160 pixels each



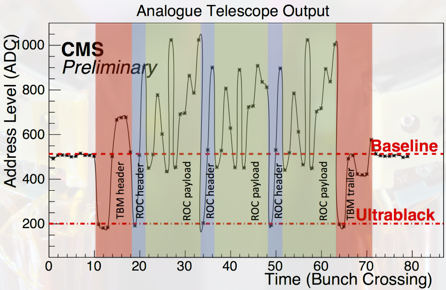


ONLINE MEASUREMENT ("FAST-OR")

- The PLT provides bunch-by-bunch luminosity with statistical precision of $\sim$ 1% every 1.5s
  - Allows for fast feedback (e.g. LHC beam optimization)
- The "Fast-OR" is a differential analog signal generated by each ROC
  - Provides information on double columns with pixels above threshold in a given 25ns bunch crossing (BX) window
  - Signal height is proportional to the number of double columns hit
- A dedicated "Fast-OR" Front End Driver (FED) histograms events with "triple coincidence" per each BX
  - i.e. where all three planes in a telescope register a hit

Offline Measurement ("Pixel")

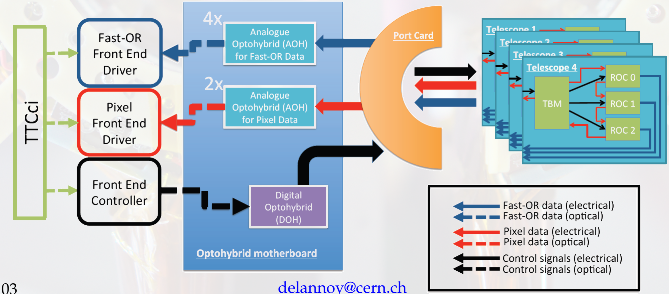
- Full pixel data is read out with a dedicated trigger at rate of $\sim$ 3kHz for additional precision studies
  - Track reconstruction allows estimates of location of the beamspot, contributions from background particles, etc.
- The Token Bit Manager (TBM) chip coordinates the read out of the three ROCs in a telescope
  - Each ROC adds a header before transmitting its payload
  - The pixel address is encoded in discrete pulse heights followed by an analogue pulse height for the collected charge



Control, Read-Out, and Front-End Electronics

- Opto-hybrid Motherboard (OMB): Converts detector's electrical signals into optical signals
- Front-End Controller (FEC): issues commands to the ROCs
- Pixel FED: reads out pixel data, decodes it, writes it via SLINK interface
- Fast-OR FED: records triple coincidences, histograms results per BX and per telescope

Control and Readout Logic of a single PLT Quarter



RELATIVE LUMINOSITY MEASUREMENT

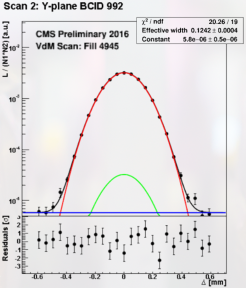
"Zero-counting" method:

- Fraction of events with no triple coincidences: $p(0)$
- $\mathcal{L} = \frac{R}{\sigma} = \mu\frac{f_{orbit}N_b}{\sigma}$
  - N_b: Number of bunches per orbit
  - $f_{orbit} = 11.22\text{kHz}$: LHC orbit frequency
  - μ: Average number of inelastic collisions
    - Poisson distribution with n observed interactions: $p(n;\mu) = \frac{\mu^n}{n!}e^{-\mu}$
    - Given $n = 0 \rightarrow \mu = -\log[p(0)]$
- Relative luminosity: $\mathcal{L} \propto \mu \propto -\log[p(0)]$

ONLINE LUMINOSITY CALIBRATION

ABSOLUTE LUMINOSITY CALIBRATION

- Assuming beams with Gaussian profiles: $\mathcal{L} = \frac{N_1 N_2 f_{orbit} N_b}{2\pi\sigma_x\sigma_y}$
  - N_1, N_2: Number of particles per bunch (beam intensities)
  - σ_x, σ_y: Effective beam sizes
- van der Meer (vdM) scan
  - Effective beam sizes can be estimated by measuring reduction in relative lumi while displacing the beams along each dimension
  - Beam separation is gradually varied and the observed rate is fit to a double Gaussian and constant term to extract beam width



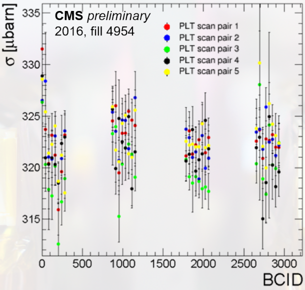
Double Gaussian fit for single BX data. Effective beam width is extracted to find overall calibration constant

Absolute Luminosity Calibration

- The visible cross-section (σ_{vis}) is defined such that

$$\sigma_{vis} = \frac{R_{max}}{\mathcal{L}} = R_{max}\left(\frac{2\pi\sigma_x\sigma_y}{N_1 N_2 f_{orbit} N_b}\right)$$

  - Proprotionality constant between the observed rate and the absolute instantaneous luminosity
  - R_{max} corresponds to the peak rate during head-on collisions
  - Beam intensities (N_1, N_2) are measured by the Fast Beam Current Transformers (FBCT) per BX

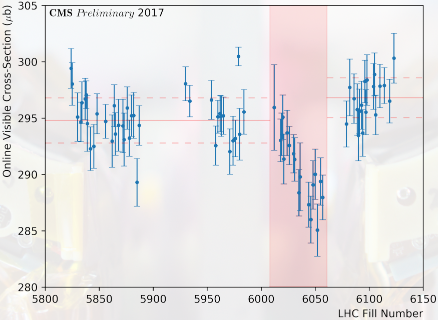


Calculated σ_{vis} per BX for each scan in 2016 vdM program

ABSOLUTE LUMINOSITY CALIBRATION

PLT Visible Cross-Section History:

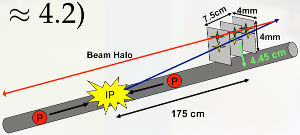
- σ_{vis} can also be determined from emittance scans
  - During each fill, beam separation is varied under nominal collisions and more quickly than in VdM scans
    - Provides per-fill detector performance monitoring
    - Downward trend highlighted in red coincides with a drop in detector efficiency



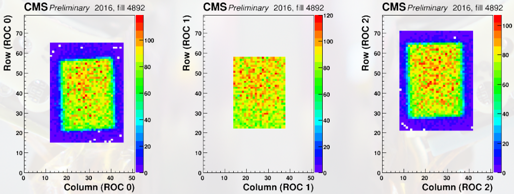
σ_{vis} calculated from mean over all BXs during 2017 LHC emittance scans

PLT Alignment

- Located 1.75m from the CMS interaction point (IP) behind Pixel endcaps ($|\eta| \approx 4.2$)



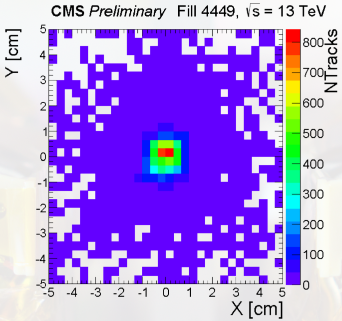
- The active area of the center sensor plane is reduced to $4 \times 4\text{mm}^2$
- Active area of outer sensor planes can be displaced such that they are aligned towards the IP
  - Alignment is adjusted to optimize rate while also reducing background ("accidental") tracks



Occupancy of events with triple coincidences in a single PLT telescope with alignment mask applied

BEAM SPOT MEASUREMENT

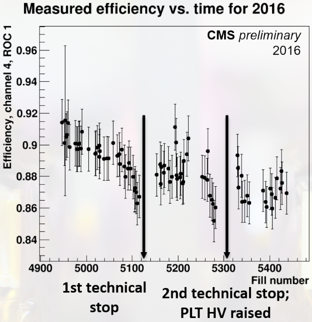
- Tracking reconstrution from offline pixel readout allows reconstruction of the beam spot position
  - Reconstructed tracks are projected back to the origin in events where there is exactly one cluster per telescope
  - Resolution at $Z = 0$ may be determined to roughly 1 cm



Beam spot in the XY plane

EFFICIENCY CORRRECTIONS

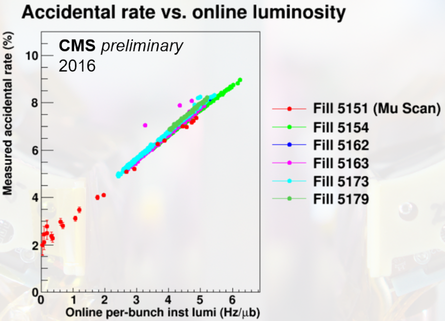
- PLT luminosity must be corrected for detector efficiency
  - Consider events with two hits in two sensor planes consistent with a potential hit in the third plane
  - Calculate fraction of events where third hit is detected
  - Provides monitoring of detector performance



Efficiency measurement per fill for a single ROC. Loss in detector efficiency resulted from increased radiation damage and was recovered by increasing the operational high-voltage

Accidental Corrections

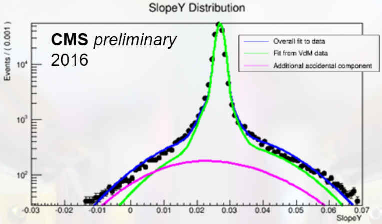
- PLT luminosity must be corrected for "accidentals"
  - i.e. triple coincidences not originating from the IP
    - Sources: beam halo, combinatorics with stray hits, etc.
  - Tracks deviating 5σ away from the mean of the reconstructed track slope distribution are considered accidentals



Rate of accidental tracks during several LHC fills as a function of instantaneous luminosity

Accidental Corrections

- Improved accidental algorithm under development
  - Track slope distribution is fit to extrapolated "clean" vdM slope distribution using maximum likelihood method



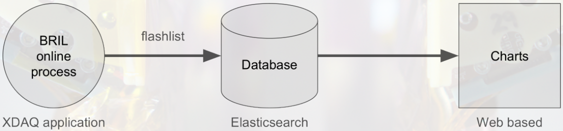
Max likelihood method with overall fit to data in blue, fit to slope distribution during VdM in green, additional accidental components at higher luminosity in purple

PLT OFFLINE CORRECTIONS

- Overall offline correction is determined from the extracted σ_{vis} and accidental and efficiency corrections
  - Determines overall normalization and "linearity" of the reported PLT online luminosity
- Accidental and efficiency correction terms are merged
  - Both contributions have a dependence on the instantaneous luminosity (i.e. linearity)
  - Includes constant term and a linear term to single-bunch instantaneous luminosity (SBIL): $p_0 + p_1 \times \text{SBIL}$

BRILDAQ

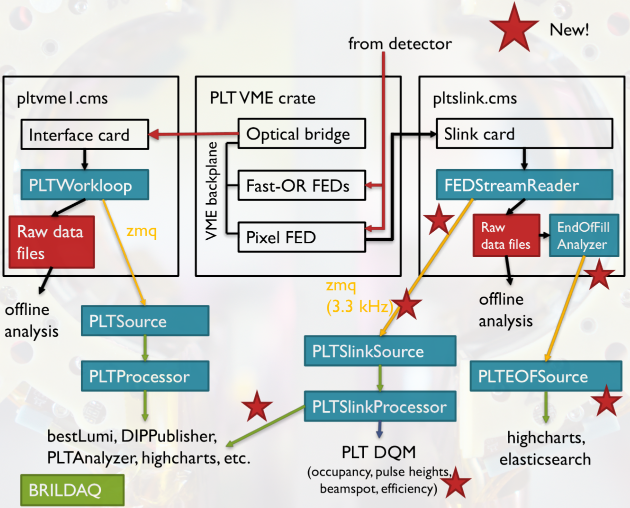
- Collection of XDAQ applications which enable real-time monitoring of BRIL data
  - XDAQ is a software platform designed specifically for the development of distributed data acquisition systems
- Uses subscriber/publisher model (b2in-eventing) for interprocess communication
  - Format of messages in BRIL data flow are predefined and agreed by subscribers and publishers
- Only accessible within CMS network
- Query fill, time interval, run number interval, etc.



BRILDAQ online monitoring setup

BRILDAQ

PLT Dataflow



PLT Fast-OR (left) and Pixel (right) dataflow from detector (center) to BRILDAQ (bottom)

WebMonitor lumi - Example Plot (Fill 6347)

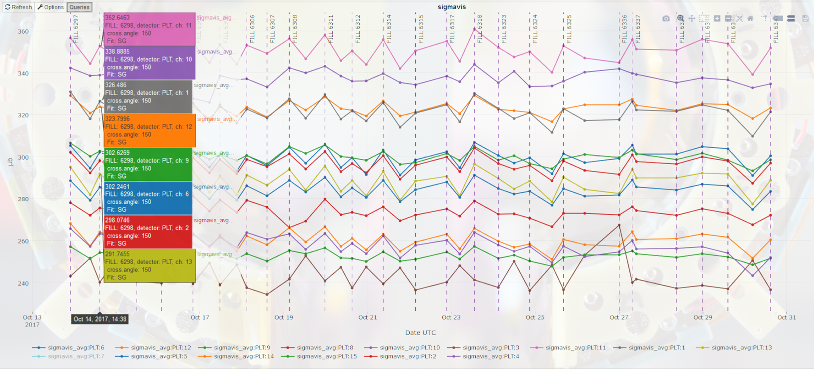
- Plots online luminosity for all detectors

Top: Luminosity and per lumi-section* with ratio plots and per 4×nibble**. Bottom: Filled BXs

* lumi section $\equiv 2^6 \times$ nibble $\sim$ 23.3s
** nibble $\equiv 2^{12} \times$LHC orbits $\sim$ 0.365s

WebMonitor vdM-PLT - Example Plot (Fill 6297-6347)

- Plots PLT σ_{vis} per fill for each channel



Per-channel PLT σ_{vis} history from LHC emittance scans

PLT SLINK Processor - Example Plot (Fill 6347)

- Plots real-time efficiencies and accidentals per-channel from pixel data
- SLINK Processor also supports email alerts and real-time DQM (occupancies, pulse heights)

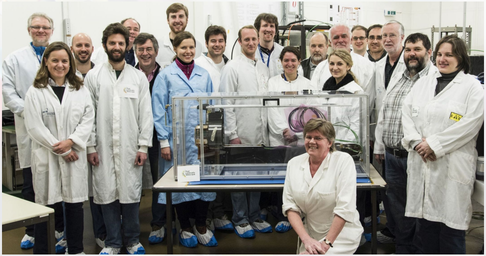
Per-channel efficiencies and accidentals vs time

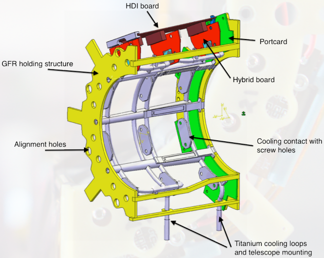
Automatic Recovery Algorithms

- Auto-recovery routines gradually deployed during 2016
- Interruptions or sudden steps in online luminosity are detected and automatically recovered after reconfiguration
  - Read-Out Chip (ROC) recovery
    - Triggers if ROC rate is below adjustable threshold wrt its neighbor ROCs
  - Token Bit Manager (TBM) recovery
    - Triggers if enbabled bits on the FED differ from ones set at beginning of run
  - Digital Optohybrid (DOH) recovery
    - Triggers if rate for an entire quadrant drops out
  - Timing and Control Distribution System (TCDS) recovery
    - Triggers if received TCDS data is bad

SiPLT History

- "SiPLT" was installed in Jan 2015 before LHC Run 2
  - Silicon sensors adopted and cooling structure implemented
  - 3D-printed titanium cooling loops using selective laser melting
  - CERN Bulletin

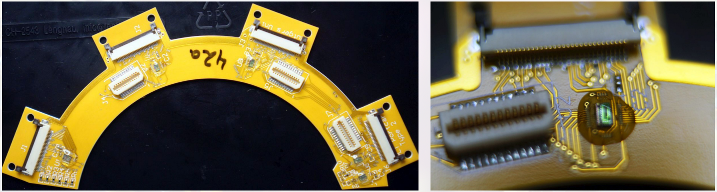




Left: SiPLT team before installation
Right: PLT "cassette" which supports one quarter of the PLT (4 telescopes) including the cooling structure

2015 Port Card Issues

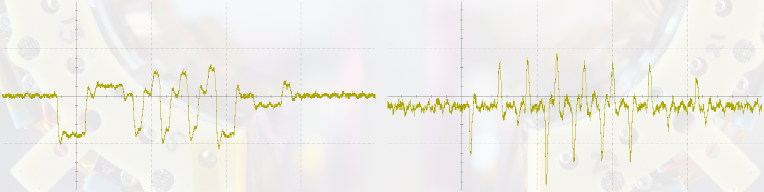
- May and Jul 2015: two telescopes were lost due to failure of LCDS chips on the port card
  - The port card manages *all* communication and control signals
  - Low-Current Differential Signal (LCDS) I^2C driver chip failure will completely bring down a telescope
    - LCDS chip failure seems correlated with numerous thermal cycles



PLT port card (left) and LCDS chip (right)

2016 Pixel Readout Issues

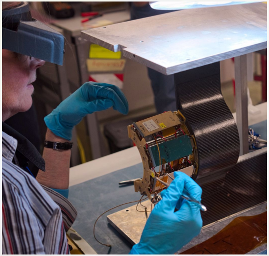
- Apr and Oct 2016: two telescopes lost pixel readout
  - Pixel readout seems attenuated and differentiated and cannot be decoded by pixel FED
  - Suspect: Analog Opto-hybrid (AOH), which converts electrical signals into optical signals

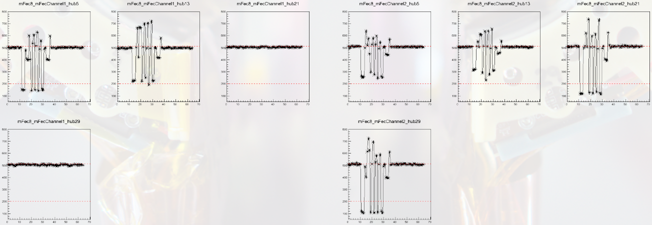


"Healthy" pixel waveform (left) vs. attenuated and differentiated pixel waveform (right)

2017 EYETS Repairs

- Faulty portcard was replaced after extensive testing
  - Both “dead” telescopes were brought back to life

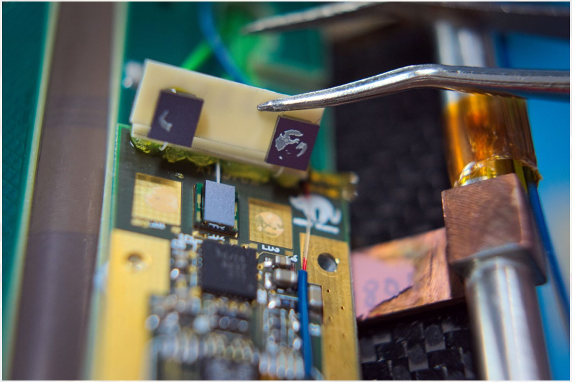




Pixel waveforms for dead telescopes (left) and recovered telescopes (right)

2017 EYETS REPAIRS

- Telescopes missing pixel readout could not be recovered
  - Repair was considered too risky
  - Similar repairs resulted in damaged components



BCM1f AOHs were ripped off during attempt to access them due to previously-applied thermal paste

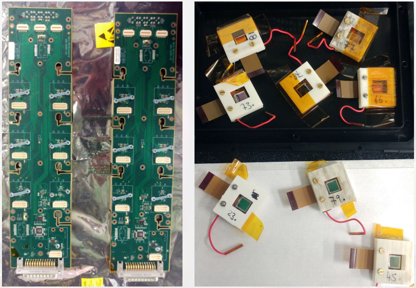
LS2 Plans

- The PLT is scheduled for repairs during Long Shutdown 2 (LS2) at the end of 2018
  - The ROCs, sensors, and other components will be close to their expected end-of-life mainly due to radiation damage
  - All components in proximity to the interaction point are scheduled to be replaced with un-irradiated spares

Disassembled PLT quadrant spare

LS2 Plans

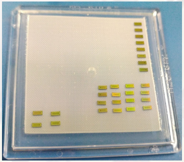
- Spare sensor planes bump-bonded to PSI46v2 ROCs are available and are in the process of being retested
- Spare OMBs are being prepared from available digital and analog optohybrid modules and slow hub chips



Left: Spare opto-hybrid motherboards (OMB)
Right: Spare sensor planes bump-bonded to PSI46v2 ROCs

LS2 Upgrades

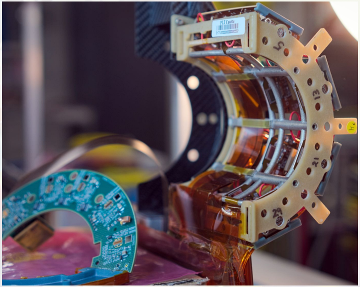
- Spare port cards
    - LCDS chips in the port cards have proven to be unreliable
    - Batch of spare LCDS chips secured
    - Spare port cards are stress tested under multiple thermal cycles in order to ensure consistent operation

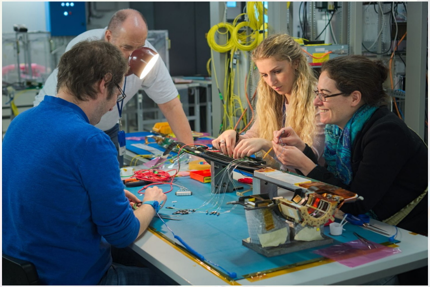



Left: Spare port cards
Right: Spare LCDS chips

2017 BRIL EYETS

2017 BRIL EYETS

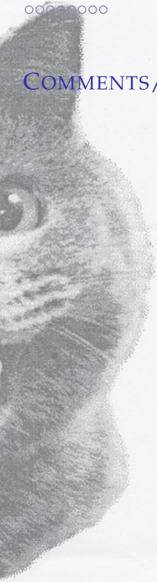




Conclusions

- PLT is providing stable online per-bunch luminosity
- Linearrity with respect to instantaneous luminosity is under study based on accidental and efficiency corrections
- Stability is being monitored online using fill-by-fill emittance scans
- PLT detector will be rebuilt for Run 3

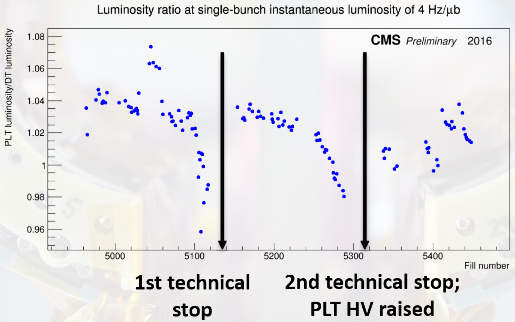
Comments / Questions



oh god how did this get in here I am not good with computers

Relative Rate Monitoring

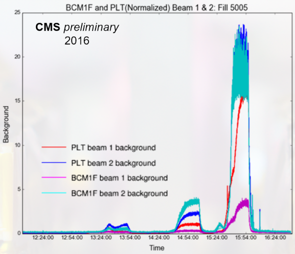
- PLT rates are periodically compared to other CMS luminosity detectors
  - Relative change in measured rates between detectors can be indicative of issues
    - e.g. radiation damage from accumulated dose



Ratio of PLT luminosity to muon rate in the drift tubes (DT) per fill at a given single-bunch instantaneous luminosity (SBIL). Drop in ratio resulted from increased radiation damage and was mitigated by increase in HVs

BEAM BACKGROUND MEASUREMENT

- Beam backgrounds can be estimated by measuring triple coincidence rates in filled non-colliding bunches
  - The PLT can employ the Fast-OR readout to monitor beam background levels in real-time
  - Background rates $\sim 10\times$ larger than Albedo afterglow contributions



Measured rate in non-colliding BXs during special LHC fill where the vacuum was intentionally worsened to induce additional background (PLT in red and blue; BCM1F detector in purple and cyan)

Status of Spare Port Cards

Port Card ID	Type	Bad Hubs	Last Tested
13	1a	29	2017-01
15	1a	13	2017-03
30a	1a	-	2017-01-29
31a	1a	13,21	
32a	1a	5,13,29	
40a	2	29	2017-02-21
41a	2	13	2016-12-16
42a	2	5,13,21,29	
51	2	29	2017-01-13

Luminosity Calculation

- At $\mu = 2.1$, ~ 0.1 tracks per BX per telescope expected
- Potential sources of uncertainty in luminosity measurement:
  - "Overlap": two (or more) tracks present in scope but only one (or not all) counted (same/adjacent double columns, ≥ 3 tracks total)
  - "Accidental": triple coincidence from the IP not caused by a real track (combinatorics, beam halo, etc.)
- "zero-counting" method: measure fraction of orbits in a nibble with no tracks
  - Lumi then proportional to $-ln < f_0 >$, where f_0 = fraction of scopes with no triple coincidences
  - Removes overlap systematics: all we care about is whether 0 or ≥ 0 tracks were present
- Calibration constant measured using VdM scan

Backup

PLT Naming/Numbering Convention