Relative non-linearity of BRIL luminometers derived from CMS mu-scans

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The CMS Beam Radiation Instrumentation and Luminosity Project (BRIL) is devoted to the simulation and measurement of beam conditions and luminosity for CMS. The project is engaged in operating and developing new detectors, compatible with the high luminosity experimental environments at the LHC. One of the BRIL tasks is the luminosity monitoring and calibration of the detectors to obtain the luminosity. For precise calibration of the luminosity it is important to understand the influence of nonlinear effects on Single Bunch Instantaneous Luminosity (SBIL) evaluated from measurements of a luminometer. A mu-scan is a beam scan performed at specific conditions suitable to evaluate the luminometer linearity.

BRIL online luminometers

1) HF (Hadron Forward) calorimeters register Cherenkov radiation in quartz fibres at particle passage [1]. HF is installed at 11 m on both sides from the interaction point. There are two types of HF: OC - occupancy counting method is used; ET - transverse energy sum algorithm.

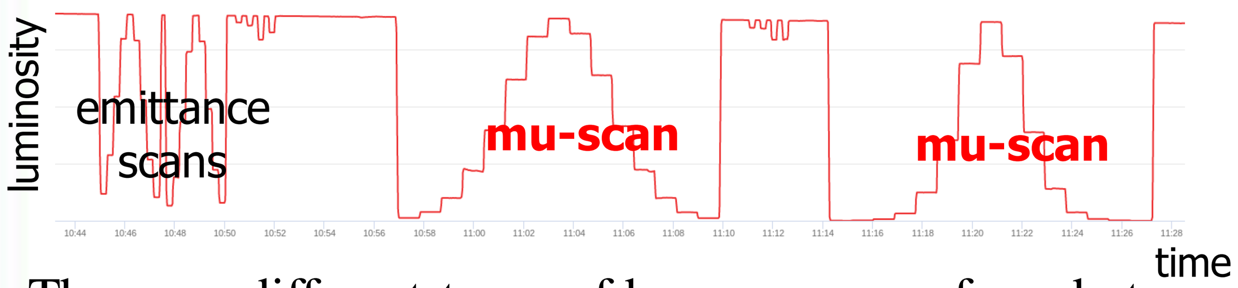
2) PLT (Pixel Luminosity Telescope) - 48 Si sensors planes arranged in 16 telescopes [2]. PLT counts three-plane coincidence ("three-fold coincidence") for luminosity measurements.

3) BCM1F (Fast Beam Conditions Monitor) - crystal silicon and diamond sensors placed on half ring PCBs. It is sensitive to both collision products and beam background [3] due to fast readout. PCVD - policrystalline diamond based; SI - Si-sensors based.

PCC method

Luminosity is evaluated from the number of pixel clusters occuring on average in a zero-bias event based on CMS pixel detector data. The probability of a given pixel being hit by two different particles from the same bunch crossing is exceedingly small => the number of hit pixel clusters per crossing is expected to be a linear function of the number of interactions per crossing [4,5].

The special beam scan in LHC fill 6847:



There are different types of beam scans perfomed at CMS when beams are scanned across each other in steps in X and in Y planes. Correspondingly, the luminosity changes at each step during a beam scan.

- Emittance scans are perfomed in every fill to provide a fast beam check during the fill.
- Special scans (so called *mu-scans*) which cover pileup from about 50 to about 0.1 are performed for non-linearity studies. These scans have more granular steps over a wider range of beam separation and better statistics at each step.

Mu-scan parameters:
- Standard beam optics, β*=30 cm, beam overlap width <20 μm;
- Scan range 5 Sigma (3.5 Sigma in emittance scans)
- 15 steps (9 steps in emittance scans)
- Per step waiting time 47 sec (10 sec in emittance scan)

Relative non-linearity calculations:

1. SBIL is calculated at each scan point: $SBIL = \frac{f_{rev} \cdot R}{\sigma_{vis}}$

   R - measured rates, σ_{vis} - calibration constant, f_{rev} - LHC revolution frequency

   σ_{vis} from 2018 van der Meer program [μb]:
   BCM1FPCVD: 203.2
   BCM1FSI: 151.9
   HFOC: 800.1
   HFET: 2445.3
   PCC: 5.8E+6

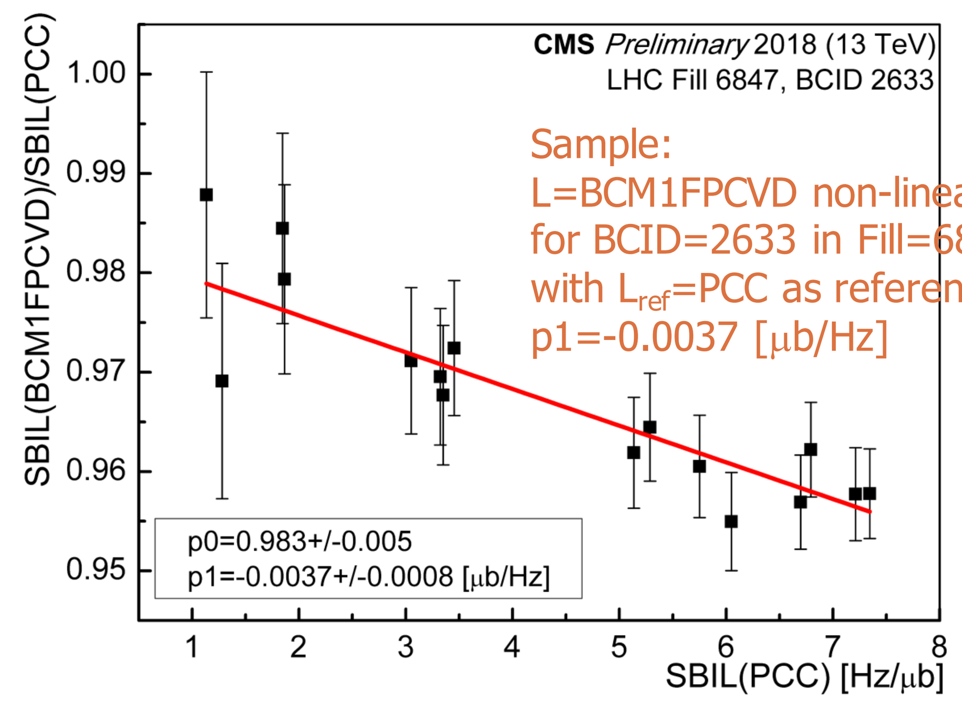
2. $Ratio = \frac{SBIL(L)}{SBIL(L_{ref})}$ **is plotted (black points) as the function of SBIL(L_{ref})**

   L_{ref} - reference luminometer (or PCC); L - any luminometer

3. Fit with a 1st order polynomial **p0+p1·*x*** (red line), fit parameters are in the legend

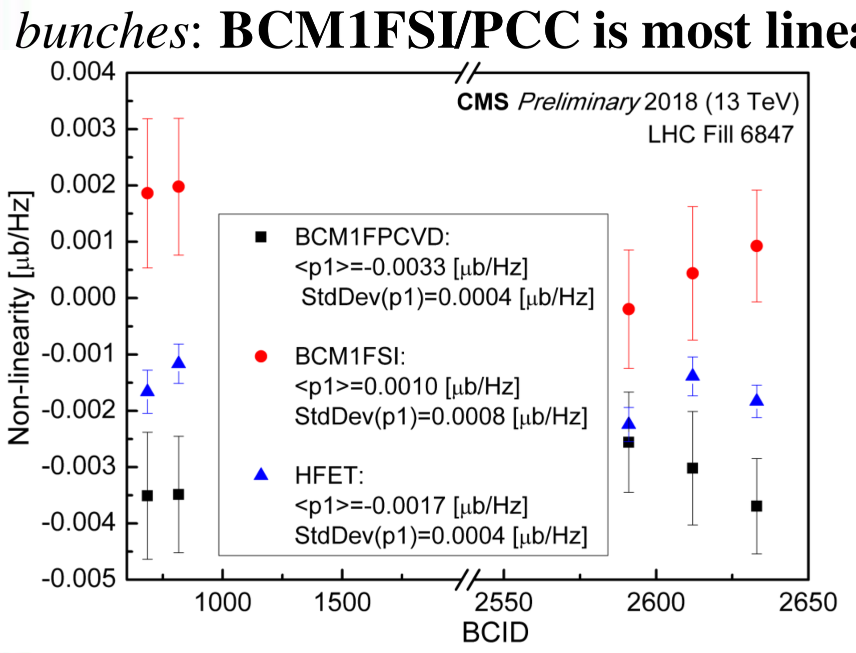
4. Slope **p1** is the quantitative characteristic of luminometers' relative non-linearity.

The reference L_{ref} is chosen to have good time stability and small dependence on pile-up, thus an almost linear response to luminosity. Where possible PCC is used as L_{ref}. The p1 parameter extracted from these fits shows the dependence of the response of luminometer L compared to L_{ref}. P1=0 corresponds to a linear relationship; values larger or smaller than zero indicate a super- or sub-linear relative response of luminometers L and L_{ref}.



Choice of the best reference scale:

- PCC is not available in all LHC fills;
- The best from among of online luminometers is decided by lowest p1 relative to PCC.
- From *Fill 6847 with 140 evenly distributed single bunches*: **BCM1FSI/PCC is most linear.**



Non-linearity≡p1
L_{ref}=PCC

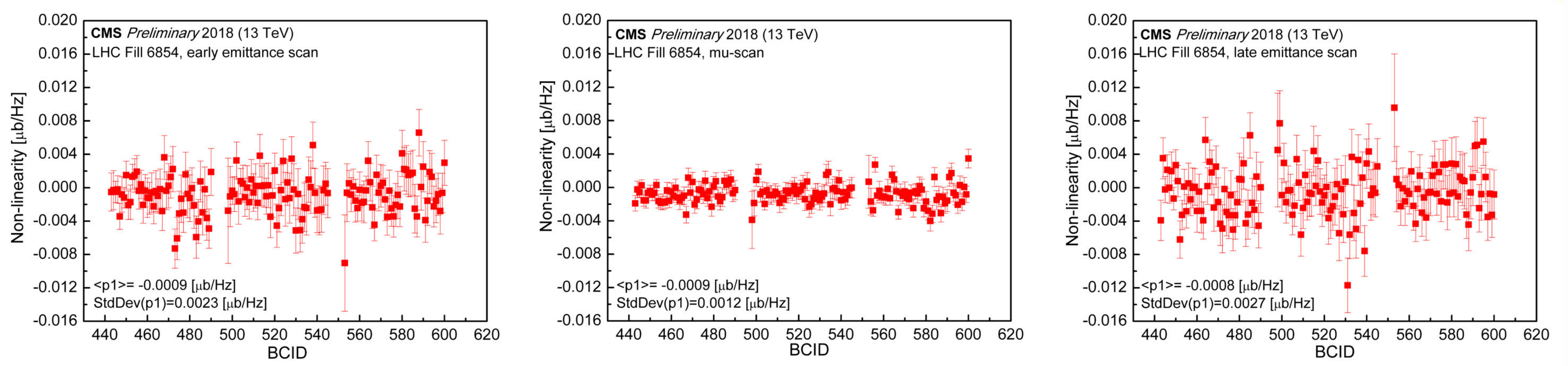
List of L:
BCM1FPCVD
BCM1FSI
HFET

PCC data is availble for 5 BCIDs

Consistency between emittance and mu-scans:

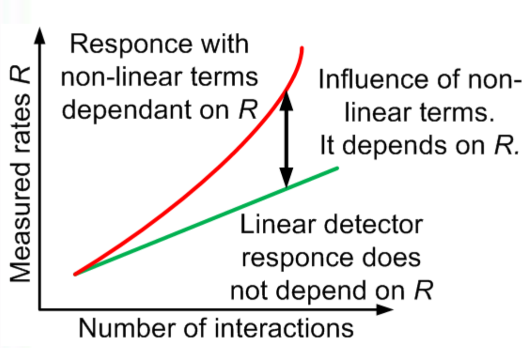
- Mu-scans was perfomed in Fill 6854 with trains of 48 bunches. Also there were two emittance scans in the beginning (early scan) and in the end (late scan) of the fill.

HFET non-linearity in emittance and mu-scans where L_{ref}=BCM1FSI, Fill 6854, trains 5-7 (numbers in the legend - for the whole fill).



- The non-linearity derived from emittance scans is in agreement with mu-scans but have larger errors.
- The advantage of BCM1FSI is that it has not significant train effect (dependence of non-linearity on the bunch position and filling scheme [6])

Why is non-linearity important?



Nonlinearity correction could be applied as follows: $SBIL_{corr} = SBIL - p1 \cdot SBIL^2$ to exclude the influence of non-linearity on measurements.

Even if p1=0.0001 the correction would be of the order of few % at high SBIL.

At HL-LHC SBIL up to 20 [Hz/μb] and pile-up ~150 are expected, so non-linearity studies will be very important to understand the detector perfomance.

Average slope <p1> [μb/Hz] (non-linearity) in 2018:

Main BCID pattern:	solo bunches		136e_48b_7e_48b_7e_48b	
Mu-scan in LHC Fill:	6847		6854	
	<p1>	StdDev	<p1>	StdDev
SBIL(PCVD)/SBIL(SI)	-0.004	0.0009	-0.0069	0.0018
SBIL(HFET)/SBIL(SI)	-0.0025	0.0008	-0.0009	0.0012
SBIL(HFOC)/SBIL(SI)¶	-0.0017	0.0008	0.0031	0.0014

Main BCID pattern:	31e_48b_7e_48b_7e_48b*			
Mu-scan in LHC Fill:	7274		7320	
	<p1>	StdDev	<p1>	StdDev
SBIL(PCVD)/SBIL(HFOC)¶	-0.0154	0.0022	-0.0157	0.002
SBIL(HFET)/SBIL(HFOC)¶	-0.0046	0.0009	-0.0046	0.0008

* e - empty BCID, b - filled BCID; ¶ - preliminary HFOC results

Summary:

- Non-linearity of luminometers has many sources as rate-dependant inefficiency, radiation damage etc.
- Relative non-linearities derived from mu-scans can be used to estimate the non-linearity correction of luminosity in physics fills.
- BCM1FSI can be used as reference scale untill Fill 6860 (after that BCM1FSI does not provide good luminosity anymore because of technical problems).
- After Fill 6860 one has to use HFOC as reference scale.
- In the future non-linearity will became especially important at HL-LHC conditions with the new generation of luminometers.

[1] B. Bilki on behalf of CMS, Proc. of 2016 IEEE NSS/MIC/RTSD (2016).
*[2] A. Kornmayer et al, Nucl. Instrum. Meth. A, **824** (2015) 304.*
[3] J. L. Leonard et al, Nucl. Instrum. Meth. A, 765, (2014), 235
[4] CMS collaboration, CMS PAS LUM-13-001, 2013.
[5] CMS collaboration, CMS AN-17-125, 2018.
[6] A. Babaev et al, presented at CMS week, 2018 Oct 1-5.