Emittance scans comparison with LHC wire scanner

CMS collaboration

Abstract

High-luminosity production at the LHC is closely linked to the size of the transverse beam emittance. However emittance measurement is challenging. It is important to use multiple methods for emittance measurement to gain confidence in the absolute value measured and to improve our knowledge of emittance evolution during “stable beams” conditions. In the proceedings to Lumi days, the potential of emittance scans for emittance measurement is studied. Comparison between the emittance measured using emittance scans at CMS in the noncrossing plane and wire scanners is presented.
EMITTANCE SCANS COMPARISON WITH LHC WIRE SCANNER
(PLOTS FOR LHC LUMI DAYS 2019 PROCEEDINGS)

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Introduction: Two BSRT calibration fills

- Beam Synchrotron Radiation Telescope (BSRT) is the only LHC instrument continuously measuring bunch by bunch emittance. Several times a year special BSRT calibration fills with 9 bunches of different emittance are performed at LHC.

LHC Fill 6592 (April 2018)
- First and last scans are 2.5 h separated, taken for comparison of the emittance evolution of the bunches measured by wire scanner (WS) and CMS

LHC Fill 7220 (September 2018)
- Two scans are 20 min separated, no evolution
- Long scan is taken for shape study and bias from the fit model measurement
Introduction: emittance calculation

• The effective beam overlap $\Sigma_{x(Y)}$ is measured from the width of the Gaussian fit to the emittance scan data in $X(Y)$ and used to calculate emittance $X(Y)$.

• In BSRT calibration fills emittance measured from emittance scans is compared to the LHC references wire scanner.

$$\varepsilon_x = \left[ \Sigma_x^2 \gamma - 2\gamma \sigma_z^2 \sin^2(\alpha/2) \right] / \left[ 2\beta^* \cos^2(\alpha/2) \right]$$

$$\varepsilon_y = \Sigma_y^2 \gamma / 2\beta^*$$

($\alpha/2$) crossing angle, $\gamma$ relativistic factor, $\beta^*$ beam optics, $\sigma_z$ bunch length.

$\varepsilon_x$ calculation requires precise measurement of bunch length, so we will only look at $\varepsilon_y$, non-crossing plane for CMS in BSRT fills.
Effective beam overlap $\Sigma_Y$ measured per bunch crossing (BCID) by different CMS luminometers in the first emittance scan of fill 6592. Single Gaussian fit was used to measure $\Sigma_Y$, no corrections applied.

Detectors (algorithms) used for luminosity measurement: the Hadron Forward calorimeter (occupancy based algorithm HFOC and transverse energy sum based algorithm HFET), the Fast Beam Condition Monitor (diamond sensors based BCM1F pCVD and silicon sensors based BCM1F Si).
Ratio of effective beam overlaps

CMS Preliminary 2018, Fill 6592, $\sqrt{s} = 13$ TeV

Ratio of effective beam overlap $\Sigma_Y$ measured by different CMS luminometers in the first emittance scan of fill 6592 with respect to HFET measurement. Agreement between detectors is better than 0.5% (except for one bunch for BCM1F Si, where agreement is ~1%).
Multiple emittance scans were done at CMS in fill 6592 close to each other in time (6 emittance scans in ~3 h). The plot shows the ratio of the emittance in Y measured from CMS emittance scan 1 and emittance scan 6 to that measured by the WS at the time close to CMS emittance scan, as a function of emittance measured by WS. ~12-22% difference is measured for two CMS luminometers (HFOC and BCM1F Si) and LHC wire scanner (WS). (Plot is similar to approved in CMS DP 2019/016).
Relative change of emittance within 2.5 h between emittance scan 1 and emittance scan 6 in fill 6592, as measured by HFOC and WS. Similar dynamics is observed by both instruments: narrow bunches blow up and wide bunch shrinks.
Double ratio of relative growth measured by HFOC emittance to that measured by WS. Assuming perfect measurement of beta* at interaction points (IPs), no change of beta* between the scans and equal beam energy at IPs, deviation of the double ratio for the bunch with low emittance from all other bunches points to the change of accuracy of CMS emittance scans or WS at emittance lower than 1.5 um. An uncertainty on double ratio is propagated using beta* uncertainty at IP4 2% (2.5%) and at IP5 1.5% (4.3%) at beta* = 30 cm (25 cm). Beam with uncertainty is taken 3% for WS and 2% for CMS.
Double ratio of relative $\varepsilon$ growth (with measured $\beta^*$)

Double ratio of relative emittance growth measured by HFOC to that measured by WS (Using measured with k-modulation, not target beta* values at IP4 and IP5). Assuming perfect measurement of beta* at interaction points (IPs), no change of beta* between the scans and equal beam energy at IPs, deviation of the double ratio for the bunch with low emittance from all other bunches points to the change of accuracy of CMS emittance scans or WS at emittance lower than 1.5 um. An uncertainty on double ratio is propagated using uncertainty on measured $\beta^*$ values at IP4 2% (2.5%) and at IP5 3.6% (3.6%) at $\beta^*$=30 cm (25 cm) [ref.1 below] and uncertainty on beam width 3% for WS and 2% for CMS.

Note: only stat. uncertainty on measured $\beta^*$ is given in the reference tables, additional 2-2.5% should be taken as syst. contributions.

One emittance scans and one long scan were done at CMS in fill 7220 close to each other in time. The plot shows the ratio of the emittance in Y measured from CMS emittance scan 1 and long scan 2 to that measured by the WS, as a function of emittance measured by WS. ~9-19% difference is measured for two CMS luminometers (HFOC and BCM1F Si) and WS for bunches with emittance >2 um and 30-37% difference for bunches with emittance <1.5 um. No beam-beam corrections applied, but effect is in the range of 1-3%. (Plot is similar to approved in CMS DP–2019/016).
Non-Gaussian bunches in fill 7220:

The long scan (15 points) of fill 7220 is suitable for testing different fit functions. E.g. double Gaussian and double Gaussian with constant term fits were applied to the data. The plot shows the fraction of the second Gaussian function in the best fit. It reaches up to about 20% for low emittance bunches, but is negligible for bunches with big emittance.
Effect of the fit function on measured $\Sigma_Y$

The long scan (15 points) of fill 7220 is suitable for testing different fit functions. E.g. double Gaussian and double Gaussian with constant term fits were applied to the data.

The plot shows the ration of measured effective beam overlap ($\Sigma_Y$) using double Gaussian or double Gaussian with constant fits with respect to that measured using single Gaussian function fit. Maximum bias of the measured $\Sigma_Y$ is 2.5%, leading to maximum bias in emittance measurement of 5%.
An example of the double Gaussian with constant term fit to long emittance scans (beams were scanned in 15 separation steps).

Fraction of the second Gaussian for this bunch with low emittance reaches about 20%, pointing that single Gaussian fit for this bunch is not ideal fit. The quality of the fit is shown by residuals distribution at the bottom of the plot.
The emittance scans in regular LHC fills with more than 2500 colliding bunches are fitted with a single Gaussian fit. The peak value, peak position, and effective beam overlap width are delivered from the fit. Here HFOC data is shown. The peak position as a function of BCID from the emittance scan in the X plane in fill 7020 is shown on the left plot and in Y plane on the right. Difference of the shapes observed for beam position in X and Y are due to the crossing angle present only in X plane for CMS.

(Plots are similar to approved in CMS-DP-2018-011, but using 2018 data).
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