Halo measurements using collimator scans

Status and plans for Run 3

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Outline

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Motivation

Many studies are very interested in having a reliable model of the LHC beam profile. In particular of the tail population for HL-LHC when a significant beam intensity is expected.

- Collimation (Crystals, hollow electron lens,...)
- Crab cavities.
- Ground motion.
- Noise effects.

Beam profile

- Ideal world: $\sigma = \sqrt{\epsilon\beta}$
- Real world:
  - Non-linearities.
  - Imperfections.
  - Chromatic beam.
  - Space-charge.
  - Beam-beam.
  - PS ripple, ground motion,...

Many ways to measure the beam profile:

- Wire scanner.
- BSRT.
- Coronograph.
- Collimator scans.

What is the actual LHC beam profile?

- Ideal world: $\sigma = \sqrt{\epsilon\beta}$
- Real world:
  - Non-linearities.
  - Imperfections.
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Many ways to measure the beam profile:

- Wire scanner.
- BSRT.
- Coronograph.
- Collimator scans.

What is the actual LHC beam profile?

We do not really know...

Beam profile using collimator scans

Procedure

- Move in one jaw of the collimator in small steps (50 microns).
- At each step, record BLM data at the collimator location.
- Calibrate BLM signal (Gy/s) with BCT intensity signal (p).

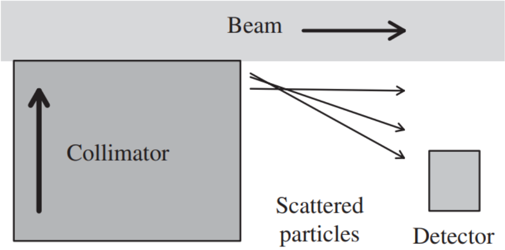

Figure: Schematic view of a collimator scan.

Pros and cons

- Most accurate method available for beam profile reconstruction.
- Slow and destructive (need to re-inject after every scraping).
- Only a few bunches at a time.

2018 measurement campaign[1]

In 2018, End-of-Fill MDs to perform collimator scrapings.

- Injection: 6 H-plane. 2 V-plane. B1/B2,
- Flat Top: 1 scraping in V-plane. B1/B2.
- Total: 18 measurements.

Reminder: 1 fill = 2 measurements (1 per beam).

[1] P. Racano Master Thesis (2018)

2018 measurement campaign (H-plane, injection)

Date	Beam	Scraping	$> 2\sigma$	$> 3\sigma$	$> 4\sigma$
30/07/2018	B1	Full	18%	5.3%	2%
			22%	7.7%	3%
			24%	8%	3%
19/09/2018	B1	Full	25%	8%	1.9%
30/07/2018	B2	Full	21%	6%	2%
			25%	10%	3%
			19%	6%	2%

Table: Fraction of particles in the horizontal plane evaluated beyond 2σ, 3σ and 4σ. Collimator sigmas $\epsilon = 3.5\mu$m

Date	Beam	Scraping	$> 2\sigma$	$> 3\sigma$	$> 4\sigma$
07/2018	B1	Full	34%	13%	6%
			27%	9%	4%
07/2018	B2	Full	30%	9%	3%
			29%	10%	3%

Table: Fraction of particles in the vertical plane evaluated beyond 2σ, 3σ, 4σ. Collimator sigmas $\epsilon = 3.5\mu$m

Beam profile modeling

Double-Gaussian

$$f(x) = \frac{I_1}{\sqrt{2\pi\sigma_1^2}} e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} + \frac{I_2}{\sqrt{2\pi\sigma_2^2}} e^{-\frac{(x-\mu_2)^2}{2\sigma_2^2}} \tag{1}$$

where $\mu_{1,2} = 0$ and $I_1 + I_2 = 1$.

Levy-Student

$$f(x) = \frac{\Gamma(\frac{n+1}{2})}{\Gamma(\frac{1}{2})\Gamma(\frac{n}{2})} \frac{a^n}{(x^2 + a^2)^{(\frac{n+1}{2})}} \tag{2}$$

However, other models can be considered (q-Gaussian, parabolic,...).

Beam profile modeling (H-plane, injection)

Date	Beam	Scraping	Double Gaussian				Levy-Student	
			I_1	I_2	σ_1	σ_2	n	a
05/2018	B1	TAILS	0.69	0.3	1.96	1.99	7.82	5.18
07/2018	B1	FULL	0.66	0.33	0.76	1.68	4.14	1.76
		FULL	0.62	0.37	0.76	1.73	3.56	1.68
		FULL	0.67	0.32	0.79	1.83	3.81	1.76
09/2018	B1	FULL	0.7	0.3	1.72	2.14	6.74	4.53
		FULL	0.7	0.3	1.65	1.72	9.41	4.92
2017	B2	FULL	0.59	0.4	0.83	0.97	8.52	2.48
05/2018	B2	TAILS	0.85	0.14	1.88	2.21	99.99	19.11
07/2018	B2	FULL	0.72	0.27	0.77	1.7	4.67	1.83
		FULL	0.61	0.38	0.77	1.52	4.88	1.99
		FULL	0.63	0.36	0.68	1.69	3	1.39

Beam profile modeling (V-plane, injection)

Date	BEAM	SCRAPING	MODEL					
			DOUBLE GAUSSIAN				LEVY STUDENT	
			I_1	I_2	σ_1	σ_2	n	a
07/2018	B1	FULL	0.69	0.3	0.92	2.07	4.1	2.09
		FULL	0.72	0.27	0.87	2.14	4.11	1.96
07/2018	B2	FULL	0.79	0.2	1.05	2.2	7.36	3.06
		FULL	0.62	0.37	0.89	1.81	4.53	2.2

Table: Values of the parameters, of both Double Gaussian and Levy-Student models, extracted from the fitted profile in the vertical plane. Collimator sigmas $\epsilon = 3.5\mu m$

Beam profile modeling (H and V-plane, injection)

Beam	Double Gaussian	
	I_1/I_2	σ_2/σ_1
B1	2.1	1.01
	2	2.33
	1.67	2.27
	2.09	2.31
	2.33	1.24
	2.33	1.04
B2	1.47	1.16
	6.07	1.17
	2.66	2.2
	1.6	1.97
	1.75	2.48

BEAM	DOUBLE GAUSSIAN MODEL	
	I_1/I_2	σ_2/σ_1
B1	3	2.25
	2.66	2.45
B2	3.95	2.09
	1.67	2.03

Table: Ratio between the intensities and variances values of the Double Gaussian model, obtained from the fits in the horizontal (left) and vertical plane (right).

- Only one measurement per beam available.

Date	BEAM	SCRAPING	MODEL					
			DOUBLE GAUSSIAN				LEVY STUDENT	
			I_1	I_2	σ_1	σ_2	n	a
07/2018	B1	FULL	0.54	0.45	0.17	0.52	2	0.31
07/2018	B2	FULL	0.77	0.22	0.24	0.59	4.96	0.58

Table: Values of the parameters, of both Double Gaussian and Levy-Student models, extracted from the fitted profile in the vertical plane. Collimator sigmas $\epsilon = 3.5\mu m$

Beam profile modeling (V-plane, Flat Top)

- Significant difference with respect to injection.
- Difference between B1 and B2.
- Only one case per beam. Need more statistics.

BEAM	DOUBLE GAUSSIAN MODEL	
	I_1/I_2	σ_2/σ_1
B1	1.2	3.05
B2	3.5	2.45

Table: Ratio between the intensities and variances values of the Double Gaussian model, obtained from the fit in the vertical plane. Collimator sigmas $\epsilon = 3.5\mu$m

Plane	Beam	I_1	I_2	σ_1	σ_2
Hor.	B1	0.66 ± 0.028	0.33 ± 0.025	1.01 ± 0.411	1.85 ± 0.178
	B2	0.64 ± 0.049	0.35 ± 0.049	0.76 ± 0.053	1.47 ± 0.297
Vert.	B1	0.71 ± 0.015	0.29 ± 0.085	0.9 ± 0.025	2.11 ± 0.034
	B2	0.71 ± 0.085	0.29 ± 0.085	0.97 ± 0.08	2.01 ± 0.195

Table: Average and standard deviation evaluated on the parameters obtained from the fitted profile, computed using the Double Gaussian model. Collimator sigmas $\epsilon = 3.5\mu$m

Which model are we currently using?

The most common model used so far to represent the beam profile has been a Double-Gaussian distribution with parameters,

$$\frac{I_1}{I_2} = \frac{0.65}{0.35}, \qquad \frac{\sigma_1}{\sigma_2} = \frac{1}{2} \tag{3}$$

- This model might work well at injection (not far from latest analysis).
- We have observed some cases with very high tail population.
- At Flat Top the model may be significantly different.

Diffusion measurements[2]

Besides tail population measurements, via collimator scans we can also determine the difussion of particles and halo repopulation.

- Several measurement campaigns between 2016 and 2018 at 6.5 TeV.
- Overpopulated tails also observed.
- It was found that the diffusion speed was higher than those measured at 4 TeV.
- This is ok for the LHC but concern arises for the efficient operation of the HL-LHC.
- Solution: implementation of active halo control methods (hollow electron lens).

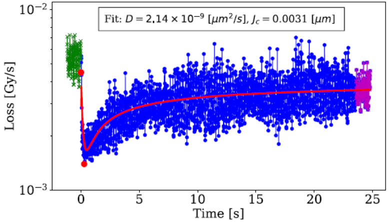

Figure: Example for recorded data and fit results for one of the outward steps.

[2] A. Gorzawski et al. Phys. Rev. Accel. Beams 23, 044802 (2020)

Defining measurement campaign for Run 3

A better understanding of the beam profile under different machine conditions is required.

- Beams: B1, B2.
- Planes: H, V, Skew.
- Cycle stages: Injection, Flat Top, Collision.
- Specific machine configurations and beam parameters.

It is important to have feedback from different teams/studies to define the best strategy.

Conclusions and prospects

Obtaining an accurate model of the beam profile (tails in particular) is very important for many studies.

- The data set available always shows overpopulated tails.
  - Need more cases in different configurations.
- Can we make any progress in a pure theoretical model?
- What is the status of new instrumentation (e.g. coronograph)?
- What are the requirements/preferences from different studies?

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- What are the requirements/preferences from different studies?

Thank you!

Date	**Data set**	**LHC Cycle**	**Intensity [p]**	**Scraping**	**Plane**	**Beam**	ϵ **[μm]**
2017	1	Injection	1.15×10^{11}	Full	H	B1	-
						B2	-
05/2018	1	Injection	3×10^{14}	Tails	H	B1	1.57
						B2	1.23
07/2018	3	Injection	1.15×10^{11}	Full	H	B1	1.90
						B2	1.73
						B1	1.72
						B2	1.58
						B1	1.61
						B2	1.81

Date	Data set	LHC Cycle	Intensity [p]	Scraping	Plane	Beam	ϵ [μm]
07/2018	2	Injection	1.15×10^{11}	Full	V	B1	1.49
						B2	1.67
						B1	1.69
						B2	1.49
07/2018	1	Injection	1.15×10^{11}	Full	S	B1	-
						B2	-
07/2018	1	Flat Top	1.15×10^{11}	Full	V	B1	1.64
						B2	1.83
09/2018	1	Injection	1.15×10^{11}	Full	H	B1	1.55