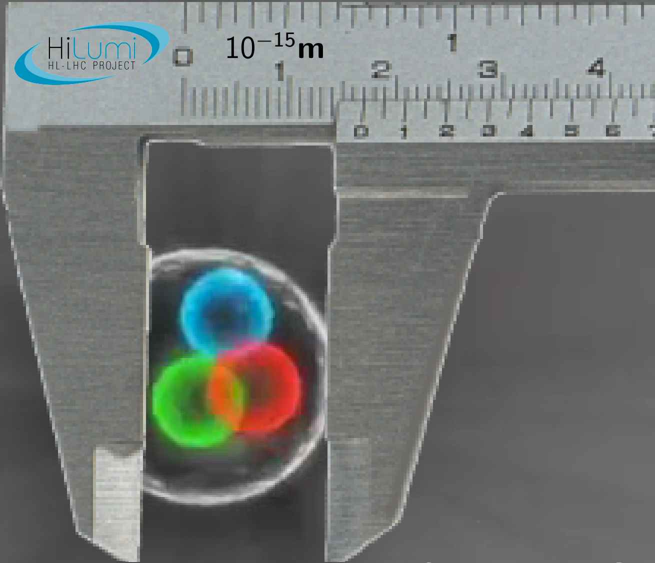


Beam size measurements requirements for HL-LHC

R. Tomás, A. Alekou, G. Arduini, R. Bruce, I. Efthymiopoulos, M. Giovannozzi, J. Jowett, L. Medina, Y. Papaphilippou, S. Papadopoulou, B. Petersen, F. Roncarolo and M. Schaumann

Contents

- ★ **Emittance accuracy:**
  (where we care about absolute value of emittance)
  - Parameters and performance
  - Performance sensitivity to emittance
  - Distortions of emittance measurements from beam dynamics
- ★ **Emittance precision:**
  (where we care about relative emittance changes, and therefore precision≈resolution in the following)
  - Sources of blow-up during fill
  - Bunch-to-bunch luminosity variations
- ★ **Ions**

Goals (protons)

★ **Nominal goal**: 250 fb^{-1}/year to reach 3000 fb^{-1}

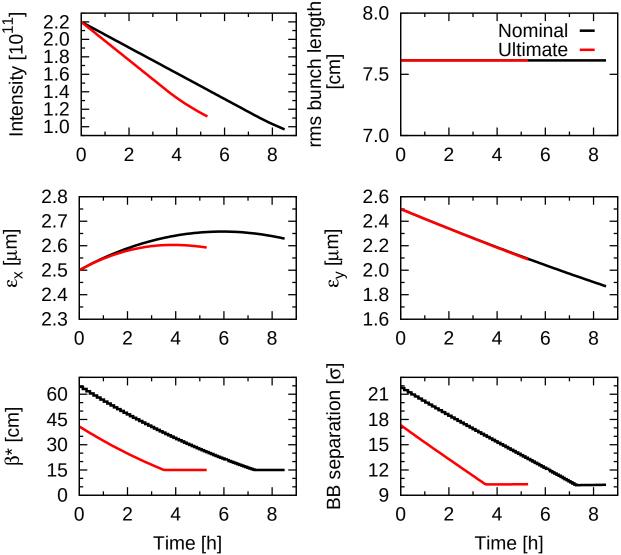
	injection	→	collision
ppb [10^{11}]	2.3	95% transmission	2.2
ϵ_{ave} [μm]	2.1	IBS+10% blow-up	2.5
BCMS	1.7	*unknown* blow-up	2.5
$N_{bunches}$	2760		

- Luminosity leveled with β^* @ 5×10^{34}cm^{-2}s^{-1}, PU=132
- 50% machine efficiency (39% stable beam time)

★ **Ultimate goal**: 320 fb^{-1}/year to reach 4000 fb^{-1}

- leveling @ 7.5×10^{34}cm^{-2}s^{-1}, PU=200
- 50% efficiency (34% stable beam time)
- Turn-around-time of 2.5 h

Physics fill (protons)



50% intensity drop.

Constant bunch length.

25% drop of ϵ_y ideally.
Blow-up sources, discussed later.

Leveling by β^*.

Beam-beam changes.

Sensitivity (@ Ultimate)

Deviations that cause **2% int. luminosity** change:

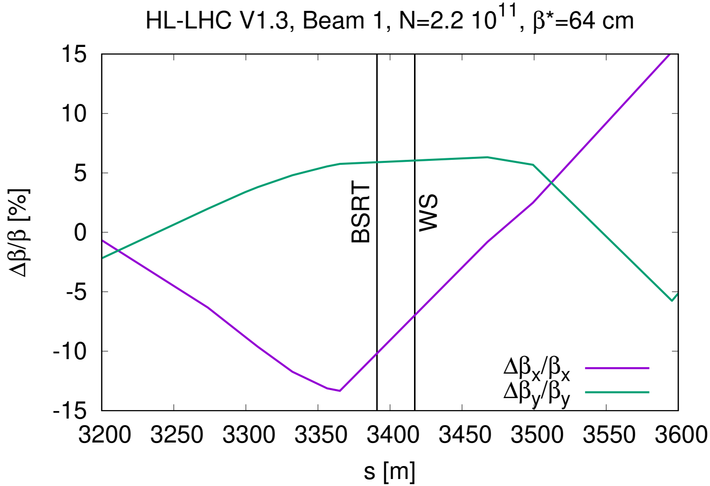
Parameter	Δ	*unit*
Turn-around-time	10	min
ppb (constant brightness)	0.09	10^{11}
ϵ (constant ppb)	0.2	μm
β^*	4	cm
Efficiency	1	%

10% change in emittance causes a 2% loss on integrated luminosity.

Knowledge of machine optics

- In Run 2 K-modulation in IR4 provided β function measurements with $\leq 2\%$ precision.
- βs in the E ramp are more challenging: $\approx$%5 precision with AC dipole measurements, or stop the ramp for K-modulation?
- Dispersion should be less of an issue $\rightarrow$ possibility to measure directly with beam size device?

β-beating from beam-beam



Beam-beam changes β at instruments within $\pm 15\%$ in the beginning of the fill.

Crabbing impact at instruments

Table: Emittance difference [%] with and without a single crab cavity with 6.8 MV at collision energy.

	L1	**R1**	**L5**	**R5**
WS - B1	33	43	44	41
WS - B2	40	32	135	138
BSRT - B1	52	67	34	31
BSRT - B2	72	58	124	130
BGV - B1	1	2	130	125
BGV - B2	0	0	150	150

Crab cavity settings will impact beam size at instruments. In ideal operation residual is negligible.

From beam-size to emittance

The following 'beam-dynamics' ingredients will be needed to convert beam size into emittance:

- ★ β function and dispersion measurements
- ★ Bunch charge, emittance and filling pattern
- ★ Crossing angle and collision offsets
- ★ Crab cavity settings

For performance **an accuracy on the emittance measurement $\leq$10% is needed**, which will require dedicated analyses.

Sources of emittance blow-up

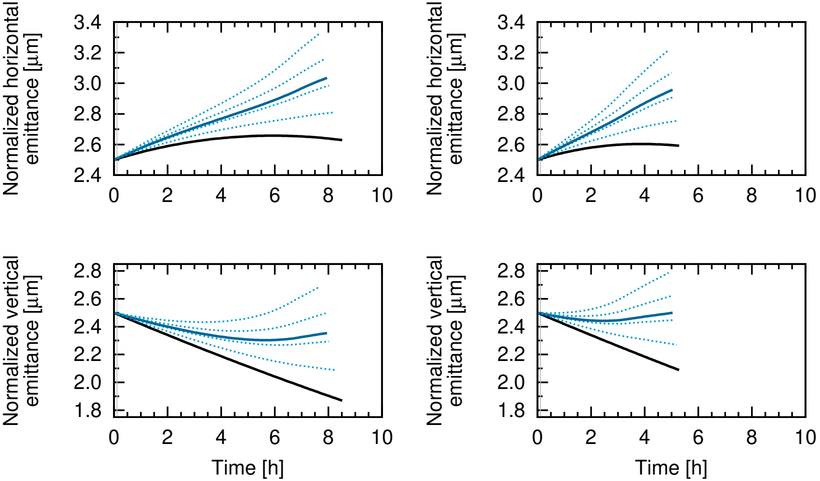
- Power converter noise
- Crab cavity noise
- Particle burn-off
- e-cloud
- Elastic scattering
- Dynamic aperture or diffusion
- etc.

A couple of illustrations more HL specific follow.

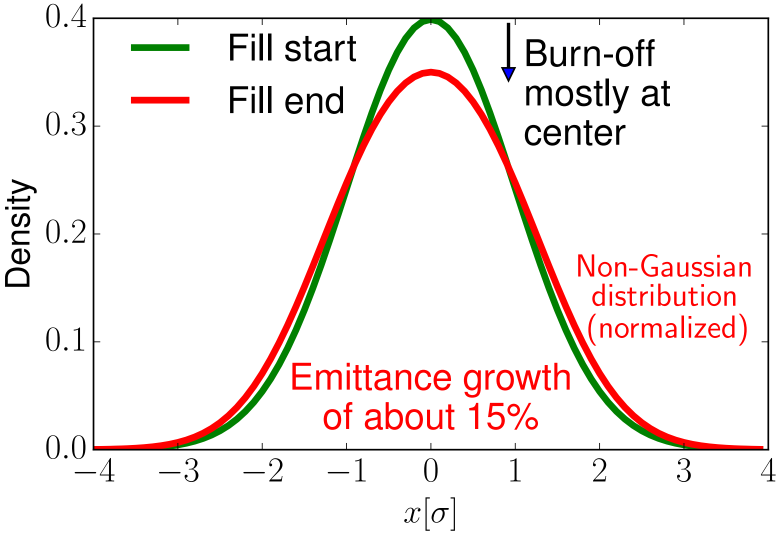
Blow-up from crab cavity noise

Current expectation in dark blue, $\Delta\epsilon/\epsilon = 10\text{-}20\%$, could be a factor 2 too pessimistic from SPS test results.

Nominal | Ultimate



Blow-up from luminosity burn-off



Bunch-by-bunch luminosity

Luminosity from 2 colliding bunches with equal β^*,

$$L \propto \frac{N_1 N_2}{\sqrt{\epsilon_{x1}+\epsilon_{x2}}\sqrt{\epsilon_{y1}+\epsilon_{y2}}} F$$

Random distributions on ϵ and N along the beams yield bunch-by-bunch luminosity fluctuations:

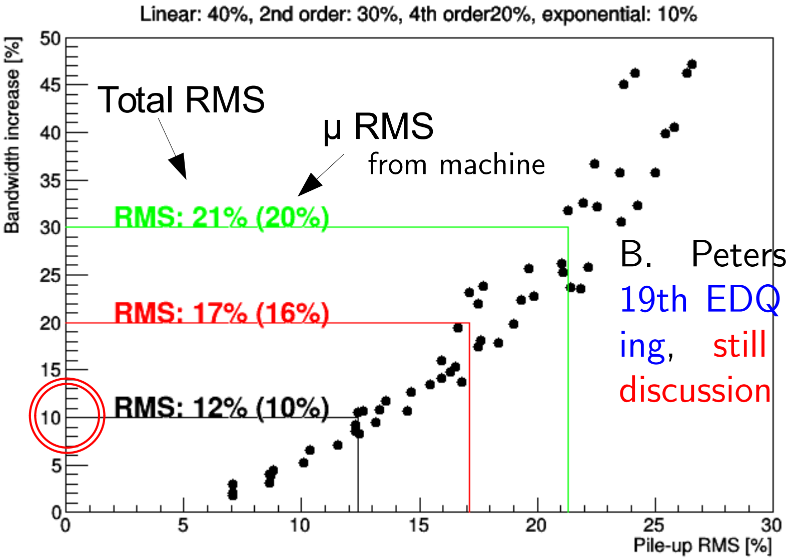
$$\left(\frac{\Delta L}{L}\right)^2 \approx 2\left(\frac{\Delta N}{N}\right)^2 + \frac{1}{8}\left(\frac{\Delta \epsilon_x}{\epsilon_x}\right)^2 + \frac{1}{8}\left(\frac{\Delta \epsilon_y}{\epsilon_y}\right)^2 + \left(\frac{\Delta F}{F}\right)^2$$

which poses concerns for the detectors.

Physics & detector aspects

- In LHC, $\mu \approx$55 event pile-up implies natural fluctuation due to the Poisson distribution of $1/\sqrt{55} =$13% (larger than machine fluctuations)
- In HL-LHC, at $\mu =$200 the natural fluctuation is $1/\sqrt{200} =$7%
- Fluctuations from beam parameters will be more relevant in HL-LHC and could cost an increased detector bandwidth or lower luminosity.

Tolerance from detectors



B. Petersen in 19th EDQ meeting, still under discussion

Tolerance for LIU & HL-LHC

Preliminary request from detectors:

- ★ $\leq$10% rms pile-up fluctuations from machine side
- ★ At 15% physics fill might be aborted
- ★ Good fill-to-fill stability of the rms fluctuations

LIU estimated $\Delta N/N \leq$3% and $\Delta\epsilon/\epsilon \leq$10%, which would imply $\Delta L/L \approx$7%, leaving some margin for changes in HL-LHC.

A **relative precision on ϵ to about 1%** will be fundamental to monitor changes over time and bunch-by-bunch variations.

Heavy-ion perf. goals (2016)

Updated request in: http://cds.cern.ch/record/2650176

- **Pb-Pb goal:** 3 nb^{-1}/one-month-run (under review) to reach 10 nb^{-1}

	injection	→	collision
ipb [10^8]	1.9	95% transmission	1.8
ϵ_{ave} [μm]	1.5	10% blow-up	1.65
$N_{bunches}$		1232	

  - Luminosity leveled with offset @ 6-7$\times10^{27}cm^{-2}s^{-1}$
  - Injection with 56 bunch trains

- **Pb-Pb special run:** 3 nb^{-1} at low ALICE magnetic field
- **p-Pb goal:** One run (190 nb^{-1} achieved in 2016)

J. Jowett's Evian 2019 slides

Requirements for ions

In general, ion operation has similar requirements to protons with a single addition:

- ★ Ion runs are short and cannot afford lengthy calibration procedures

An accuracy on emittance measurement below 10% with ions should be achievable without lengthy calibration procedures.
About 1% precision in relative changes over time and bunch-by-bunch is also needed.

Summary

- Emittance measurement accuracy below 10% is required for performance
- A precision of about 1% for relative changes over time or bunch-by-bunch measurements is needed.
- Access to the actual 2D distribution will be important to understand growth mechanisms
- The required time scale is about 1 minute (far from the 10 ms requested for LHC).
- In ions lengthy calibration procedures must be avoided.

Back-up slides

Wire scanner beam charge limits

In Run 2 wire scanner limits on beam charge were:

- 270×10^{11} protons at injection
- 16×10^{11} protons at 6.5 TeV

Larger bunch charge in HL-LHC would reduce the max. number of bunches.

Raymond Veness addresses possible mitigations.

Emittance blow-up from burn-off