Luminosity stability and control at LHC

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Outline

- Acceptable luminosity degradation
- Luminosity formula and variations
- Sensitivity to beam offset
- Beam-beam considerations
- Measuring beam motion at IP

This being a quick first order view of the subject.

Acceptable luminosity degradation

- We must justify a investment of 2 billion SF
- Get and keep nominal luminosity

$$\frac{\mathcal{L}}{\mathcal{L}_o} > 0.98 \quad (1)$$

(forgetting the decay with time)

Luminosity of two identical round gaussian beams

$$\mathcal{L}_o = k_b f_r N_{b1} N_{b2} \frac{1}{4\pi\sigma^4} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-\frac{x^2}{2\sigma^2} - \frac{y^2}{2\sigma^2}} \tag{2}$$

which integrates to

$$\mathcal{L}_o = \frac{k_b f_r N_{b1} N_{b2}}{4\pi\sigma^2} = \frac{k_b f_r N_{b1} N_{b2}}{4\pi\epsilon\beta} \tag{3}$$

with

- k_b the number of bunches
- f_r the revolution frequency
- N_b the nb of protons/bunch
- σ the beam size at the crossing point (IP)
- ϵ,β the emittance and the beta function at the IP

Intensity variations

- Bad for integrated luminosity => keep $\frac{\delta N_b}{N_b} < 2\%$
- Affects beam-beam tune shift

$$\xi_{head-on} = \frac{N_b r_o}{4\pi\epsilon_n} \qquad \xi_{long-range} = \frac{N_b r_o}{2\pi}\frac{\beta(s)}{\gamma d^2} \tag{4}$$

- $\xi_{long-range}$ dominant
- 10% variations of N_b acceptable beam-beam-wise
- Opposite IP1/IP5 ensures equal luminosity (N_i/N_j collide together at both locations)

Emittance variations vs. luminosity

For small beam size differences

$$\mathcal{L} \sim \frac{1}{\sqrt{\sigma_{x1}\sigma_{x2}\sigma_{y1}\sigma_{y2}}} \tag{5}$$

As most likely $\sigma_{x1,2} = \sigma_{y1,2}$ (residual coupling), we can write

$$\mathcal{L} \sim \frac{1}{(\epsilon_1 \epsilon_2)^{1/4}} \tag{6}$$

Therefore

$$|\frac{\mathcal{L}}{\mathcal{L}_o}| < 2\% \quad <=> \quad \frac{\delta\epsilon_{1,2}}{\epsilon} < 4\% \quad \text{one beam} \tag{7}$$

$$|\frac{\mathcal{L}}{\mathcal{L}_o}| < 2\% \quad <=> \quad \frac{\delta\epsilon_{1,2}}{\epsilon} < 2\% \quad \text{both beams} \tag{8}$$

Beam-Beam:

Only $\xi_{head-on}$ depends on ϵ, so $\frac{\delta\epsilon}{\epsilon} \sim 10\%$ would be acceptable

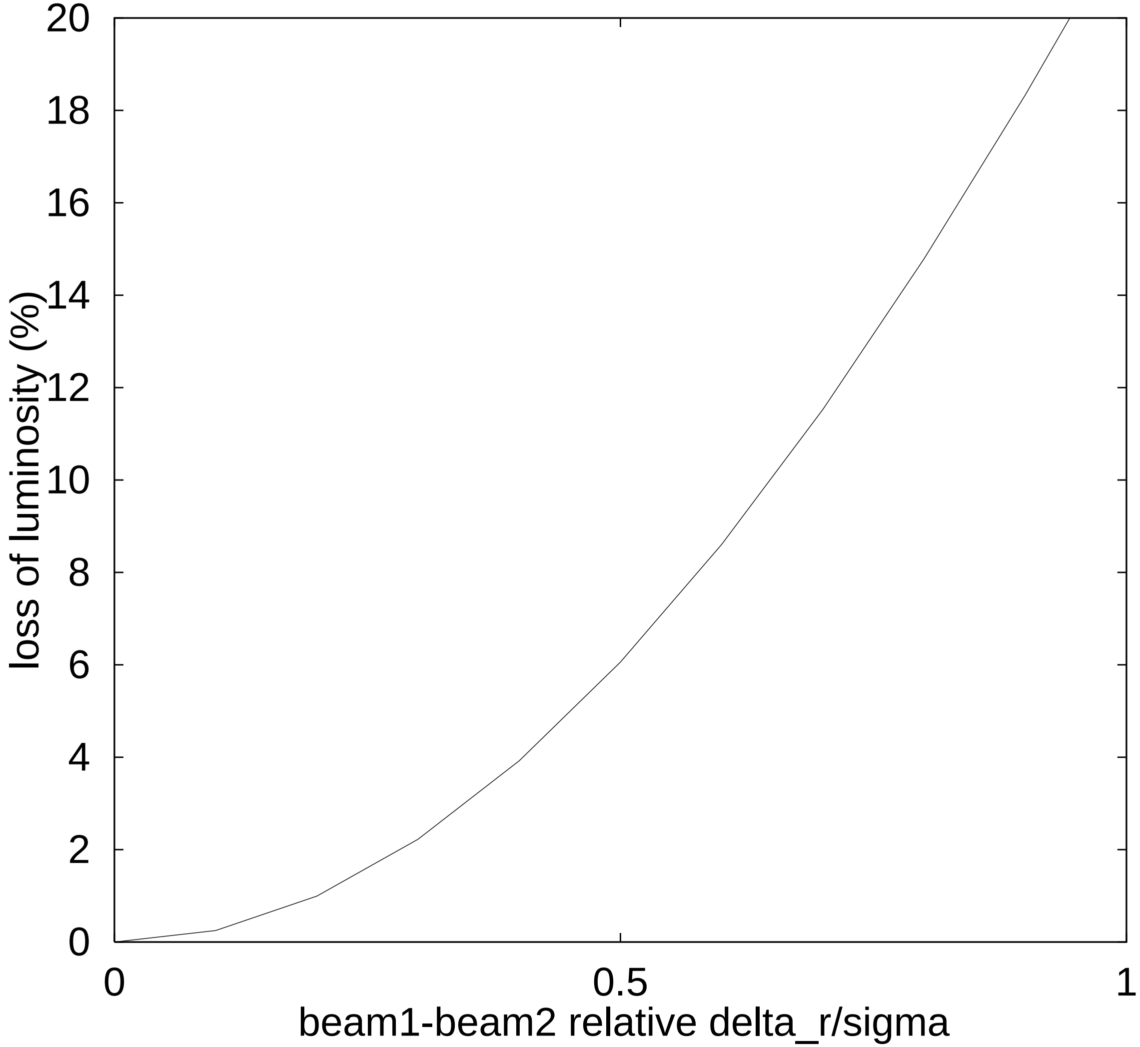
Luminosity loss with beam offset at IP

Apply a radial relative radial offset δ_r: in Eq. (2)

$x^2 + y^2 -> (x - \delta_r)^2 + y^2$

$$\frac{\mathcal{L}(\delta_r)}{\mathcal{L}_o} = \frac{1}{\pi\sigma^4} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-\frac{1}{\sigma^2}(x^2+y^2-x\delta_r+\delta_r^2/2)} \quad (9)$$

no primitive, integrate numerically


20
18
16
14
12
10
8
6
4
2
0
loss of luminosity (%)
0
0.5
1
beam1-beam2 relative delta_r/sigma

Luminosity loss with beam offset at IP, continued

1D displacement relative to average orbit $\Delta_{x,y} = \delta_r/2\sqrt{2}$

With $\beta = 0.5$ m in collision $\sigma = 16\ \mu$m.

Then from the figure

$$\frac{\mathcal{L}(\delta_r)}{\mathcal{L}_o} = 2\% <=> \delta_r = 0.28\sigma <=> \delta_{x,y} \leq 0.1\sigma = 1.6\mu\mathrm{m} \quad (10)$$

$$\frac{\mathcal{L}(\delta_r)}{\mathcal{L}_o} = 5\% <=> \delta_r = 0.45\sigma <=> \delta_{x,y} \leq 0.1\sigma = 2.6\mu\mathrm{m} \quad (11)$$

The orbit default at the IP must be controlled to $\sim 1\mu$m

Beam offset and resonance excitation

- Whatever working point is used, the tune area will be crossed by 13th order resonances
- With head-on beams, this resonance is not excited (and marginally with large separations)
- Observed at the SPS collider with slight separation at IP
- It is wise to control the separation below $\approx 0.3\sigma$

Coherent bunch oscillations

This would induce luminosity losses, but in the abscence of damping would also kill the beam sooner or later (J.Gareyte). Therefore

- Either beam-beam does enough damping or
- The feedback must be used at high energy too
- => Not linked to luminosity or to luminosity controlled feed-back
- Therefore, no need of bunch by bunch luminosity measurement for this case

Intermediate Summary

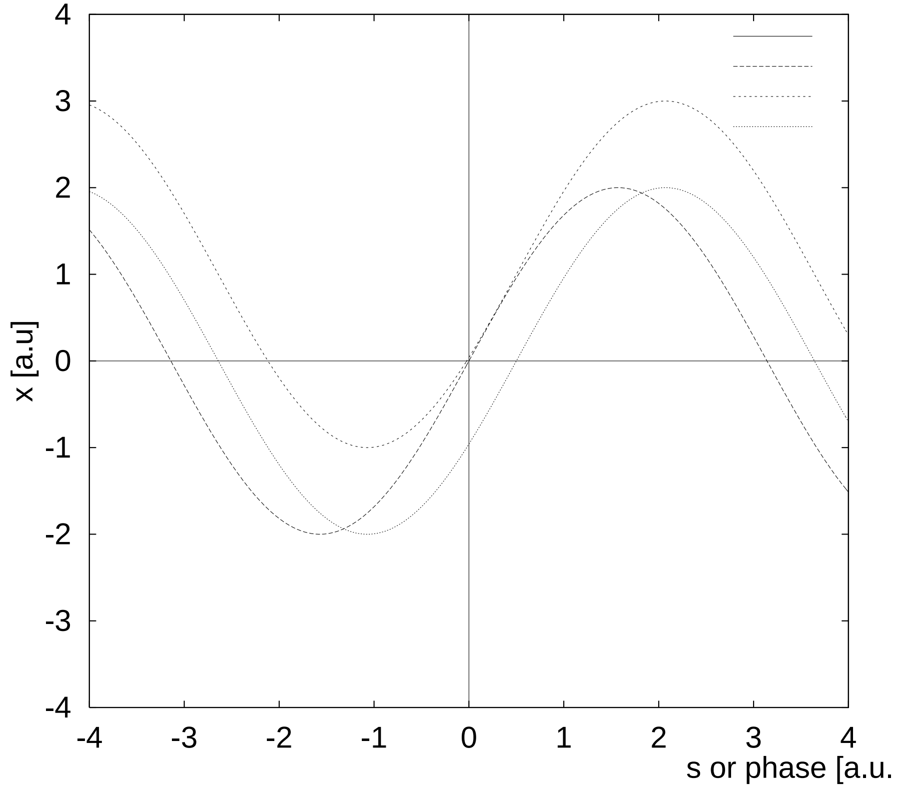
A specification might be:

Control and measure

- N_b to $\sim 2\%$ – Fast BCT's ?
- ϵ_n to $\sim 2\%$ – ?
- $\delta_{x,y}$ at IP to $\sim 1\ \mu$m – Local measurements

Measuring the beam position at the IP

- Need $\delta_{x,y} \approx 1\mu$m, but also $\delta'_{x,y} = \frac{\delta_{x,y}}{\beta} = \frac{10^{-6}}{0.5} \approx 2\mu$rad
- $\Delta x_{max} = \delta x \sqrt{\frac{\beta_{max}}{\beta_{ip}}} = 10 \times \sqrt{s \frac{4700}{0.5}} = 970$ mum $\approx 1\sigma_{max}$



Measuring the beam position at the IP - continued

- Most likely experiment might deliver the beam position every second to the requested relative precision of 1 micron
- If not, instrument the TAS?
- But of course, we shall first collide
- ’during the first days’, can we envisage to have a movable screen, next to the TAS? It would be used with pilot bunches or batches of adjusted intensity (see also next slide).

Measuring the beam angle at the IP - continued

- Use a detector in the TAN, located at 150m away from the IP
- Need a spatial resolution $\sigma_{TAN} = l_{TAN}\delta x'_{IP} = 1.5 \cdot 10^5 \times 2 \cdot 10^{-6} \approx 0.3$ mm
- The shower of the neutral spot in the TAN has a width of 10-20 mm
- With width fluctuations of $\sigma_{shower} \sim 10$ mm , integrating $n_{ev} = 10^6$, we get centroid fluctuations

$$\sigma(x, y) \approx \frac{\sigma_{shower}}{n_{ev}^{1/2}} \approx 0.01\mathrm{mm} \tag{12}$$

- Therefore limited by the segmentation of the detector
- With segments of 3mm the resolution shall be 0.3mm – DOABLE
- This detector could be used when using screens too

Measuring the beam at the IP - continued

- The neutrals fly straight
- No disturbance because of triplet defaults
- BPM's in the triplet might be biased by radiation (aging, electrostatic) and by multipacting
- Knowing the beam position and angle might even help to understand the alignment (and therefore the aperture) of the triplet

Summary

- The luminosity shall be measured/controlled to 1-2%
- The most critical parameter is the IP beam positions (x,x',y,y')
  need $\delta x = \delta y \approx 1$ μm and $\delta x' = \delta y' \approx 2$ μrad
- We propose to use a detector in the TAN to measure (x',y')
- We shall ask the experiments to provide x and y
- We see at present no need for luminosity measurement at the bunch level
  An exception might the understanding of PACMAN bunches - this would require a time resolution of $\sim$ 10 bunches or 250 ns.