# Head-on Compensation in LHC

Walter Scandale & Frank Zimmermann

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# luminosity

$$L = f_{rev} \frac{n_b N_b^2}{4\pi\sigma^2} F_\phi$$

$$\approx f_{rev} \frac{n_b N_b}{4\pi} \frac{\gamma}{\beta^*} \frac{N_b}{\varepsilon_N} F_\phi$$

LHC normalized emittance is limited by mechanical acceptance at injection

$$\approx f_{rev} n_b N_b \frac{\gamma}{r_p} \frac{\Delta Q_{bb}}{\beta^*}$$

head-on tune shift / IP is limited to ~0.005 w/o compensation head-on beam-beam tune shift / IP

$$\Delta Q_{bb} \approx -\frac{r_p}{4\pi}\frac{N_b}{\varepsilon_N}F_{geom}$$

by compensating this tune shift, the e-lens would allow for larger beam brightness $N_b/\varepsilon$

however the brightness is also limited by space charge in PS booster and PS:

$$\Delta Q_{sc} = -\frac{r_p}{4\pi}B_f\,\frac{1}{\beta_p\gamma_p^2}\frac{N_b}{\varepsilon_N}$$

$\Delta Q_{sc}$~-0.5 in PSB for ultimate LHC

# injector upgrade

- head-on compensation:
  can increase LHC luminosity ***only if***
  beam brightness in injectors is also
  increased
- new injectors: SPL + PS2 + enhanced SPS:
  designed to increase the LHC beam
  brightness two times above “ultimate”
- for constant total current in LHC:
  peak luminosity ~2x ultimate,
  but beam lifetime ~1/2 ultimate

# average luminosity

$$L_{ave} = \hat{L} \frac{\tau_{eff}}{\left(\tau_{eff}^{1/2} + \tau_{turnaround}^{1/2}\right)^2}$$

$$\tau_{eff} = \frac{n_b N_b}{n_{IP} \hat{L} \sigma_{tot}}$$ effective decay time

$$T_{run,optimum} = \sqrt{\tau_{eff} T_{turnaround}}$$

optimum run time

# example: 2x ultimate peak-$L$, total beam current constant

| parameter | symbol | nominal | ultimate | ultimate with h-o compensation |
|---|---|---|---|---|
| transverse emittance | $\varepsilon$ [$\mu$m] | 3.75 | 3.75 | 3.75 |
| protons per bunch | $N_b$ [$10^{11}$] | 1.15 | 1.7 | 3.4 |
| bunch spacing | $\Delta$t [ns] | 25 | 25 | 50 |
| beam current | I [A] | 0.58 | 0.86 | 0.86 |
| longitudinal profile | | Gauss | Gauss | Gauss |
| rms bunch length | $\sigma_z$ [cm] | 7.55 | 7.55 | 7.55 |
| beta* at IP1&5 | $\beta*$ [m] | 0.55 | 0.5 | 0.5 |
| full crossing angle | $\theta_c$ [murad] | 285 | 315 | 315 |
| Piwinski parameter | $\phi=\theta_c\sigma_z/(2*\sigma_x*)$ | 0.64 | 0.75 | 0.75 |
| peak luminosity | $L$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | 1 | 2.3 | 4.6 |
| events per crossing | | 19 | 44 | 176 |
| initial lumi lifetime | $\tau_L$ [h] | 22 | 14.4 | 7.2 |
| effective luminosity ($T_{turnaround}$=10 h) | $L_{eff}$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | 0.46 | 0.91 | 1.06 |
| | $T_{run,opt}$ [h] | 21.2 | 17.0 | 8.5 |
| effective luminosity ($T_{turnaround}$=5 h) | $L_{eff}$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | 0.56 | 1.15 | 1.26 |
| | $T_{run,opt}$ [h] | 15.0 | 12.0 | 6.0 |

→ average luminosity increases only by 10-20%

# summary

- head-on compensation + injector upgrade could double LHC beam brightness
- this increases peak luminosity by factor 2, if the total LHC beam current is kept constant (1/2 number of bunches)
- resulting increase in average luminosity is only ~10-20%, due to two times shorter luminosity lifetime; peak #events / crossing increases 4 times