Luminosity reduction due to phase modulations at the HL-LHC crab cavities

E.Yamakawa[1], P. Baudrenghien[2], R. Calaga[2], A. C. Dexter[3]

[1]JAI/Oxford University

[2]CERN-BE-RF

[3]Lancaster University

April 1, 2019

Introduction

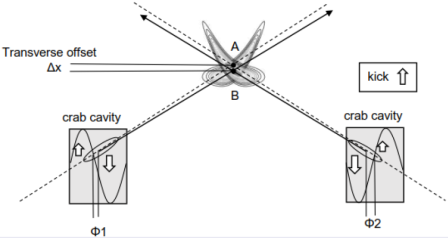
- Crab cavities are installed around IP1 & IP5 to compensate geometric reduction in luminosity due to the beam crossing angle at the IP.
- There will be two crab cavities per beam on either side of IP1 and IP5. Sixteen cavities in total.

Table 1: List of parameters for the baseline HL-LHC (HL-LHC V1.2 [1])

Proton energy at collision	7 TeV
Number of protons in a bunch N	2.2×10^{11} ppb
Number of bunch n_b	2748
r.m.s. bunch length ($4\sigma_z$)	1.2 ns
Longitudinal emittance	2.5 eVs
Transverse normalized emittance $\epsilon_{n(x,y)}$ (r.m.s)	2.5 μm
Full crossing angle	510 μrad
Nominal crab cavity voltage	3.4 MV/cavity
Crab cavity RF frequency	400.79 MHz

Introduction

- Existing klystron power is insufficient to run the HL-LHC with the current LLRF control algorithm.
- New algorithm (Full-Detuning) avoids this limitation by accepting a phase modulation of accelerating RF cavity, which is operational since 2017 [2].
- Crab cavity (C.C) cannot follow the phase modulations (up to 100 ps pk-pk), resulting in a phase error w.r.t the individual bunch centroid.
- Phase errors at C.C creates significant sinusoidal bunch distortions at the IP.



Investigate the impact of phase modulations on the peak luminosity

Table of Contents

Analytical solution of bunch distributions

1. Define Gaussian bunch distribution at C.C: $\rho_{c.c}(x_{c.c}, y_{c.c}, z_{c.c})$
   - A thin crab kick: $\delta x'_{c.c} = \frac{eV_1}{E_s}\sin(kz_{c.c} + \phi) \quad (\delta x_{c.c} = 0)$
2. Transport the bunch from C.C to IP: $\rho_{IP}(x_{IP}, y_{IP}, z_{IP})$
   - $\pi/2$ phase advance between C.C to IP
   - $\alpha_{IP} = 0$
3. Rotate coordinate system at IP by $\theta/2$: $\rho_{IP}(\tilde{x}_{IP}, \tilde{y}_{IP}, \tilde{z}_{IP})$

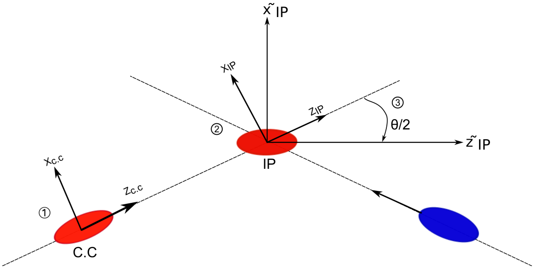


Figure 1: Coordinate system around the IP.

Details are presented in [3].

Bunch distributions without phase modulations at the IP

Table 2: Twiss parameters of baseline optics in the HL-LHC (HL-LHC V1.2 [1]).

$\beta^*_{x,y}$ at IP5	0.20, 0.20 m
$\beta_{x,y}$ at C.C before IP5	2453, 2160 m
$\alpha^*_{x,y}$ at IP5	0 , 0
$\alpha_{x,y}$ at C.C before IP5	-14.0, -36.7

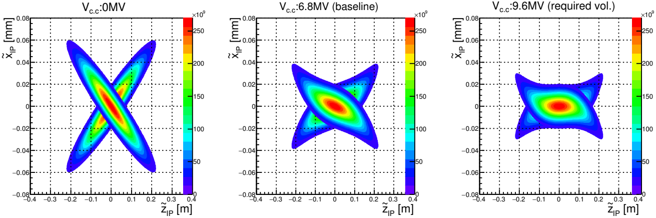


Figure 2: Bunch distributions at IP with crab voltages at 0 MV (without crab cavity), 6.8 MV (baseline) and 9.6 MV (required for full correction) without phase modulations.

- Voltages quoted are for two CCs (total voltage on one IP side).
- The baseline gives partial compensation of the crossing angle. See [4].

Bunch distributions at IP with coherent phase modulation

- The Full-Detuning phase modulation depends on the filling pattern. With same filling scheme in both rings, the phase modulation of colliding bunches are identical in IP1 and IP5

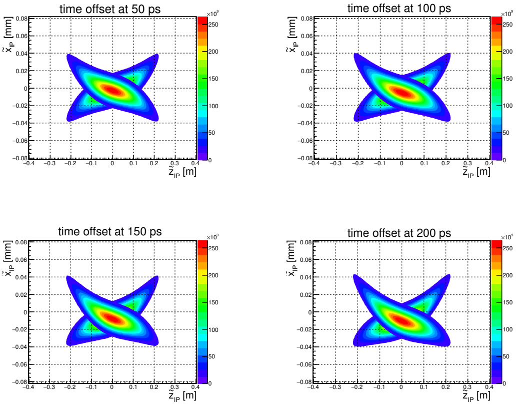


Figure 3: Bunch distributions at IP with crab voltages at 6.8 MV with phase modulations.

Luminosity calculation with phase modulations

Translating bunches from the IP along the beam line (z_{IP}): $z_{IP} \pm ct$

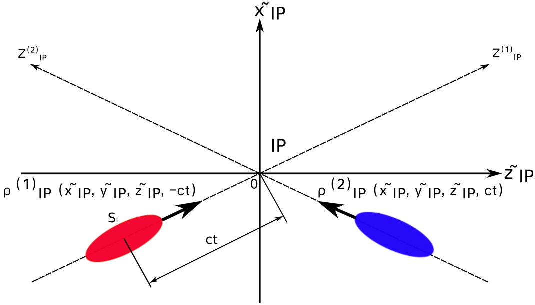


Figure 4: Schematic view of colliding pairs around the IP.

Integrated peak luminosity:

$$L = 2 \cdot \cos^2 \frac{\theta}{2} N_1 N_2 f_{rev} n_b \int \int \int \int_{-\infty}^{\infty} \rho_{IP}^{(1)} \left(\tilde{x}_{IP}, \tilde{y}_{IP}, \tilde{z}_{IP}, -ct\right) \cdot \rho_{IP}^{(2)} \left(\tilde{x}_{IP}, \tilde{y}_{IP}, \tilde{z}_{IP}, ct\right) d\tilde{x}_{IP} d\tilde{y}_{IP} d\tilde{z}_{IP} d(ct). \tag{1}$$

N_1, N_2: number of protons in bunches, n_b: number of bunches

Table of Contents

Linear transfer map from MADX

- Twiss parameters and first-order transfer map are created by MADX
- Transfer-map: IP1&IP5, 2 main accelerating RF cavities around IP4, one pair of C.C around IP1 and IP5
- HL-LHC V1.2 [1] (round optics $\beta_x^* = \beta_y^*$)

PYTRACK simulations

- Inject protons (10^5) at IP1 and observe bunch distributions at IP5
- Transverse initial bunch distribution: Gaussian
- Longitudinal initial bunch profiles: Gaussian and q-Gaussian (n=2.5) are generated by BLonD code [5].
- q-Gaussian profile is a close match to the measured LHC longitudinal profile. The definition of q-Gaussian is in [4].
- Ramping up crab voltage over 1000 turns (two synchrotron periods, F_s=23Hz, F_{rev}=11kHz) linearly to keep quasi-static synchrotron motion

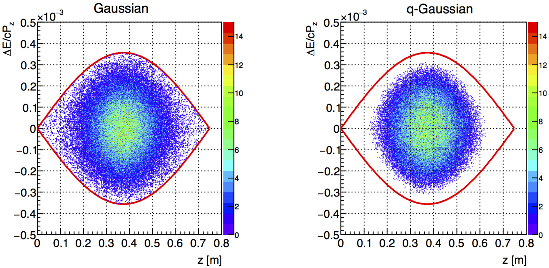


Figure 5: Longitudinal initial bunch distributions generated by BLonD.

Bunch distributions with coherent and incoherent phase modulations

- Coherent phase modulations: Identical filling pattern B1-B2
- Incoherent phase modulation can be caused by imperfect phase alignment of the crabbing and uncrabbing cavity pairs or by different fillings for the two beams (not planned).
- The incoherent phase modulation results in a larger degradation in luminosity because the cores of the two colliding bunches do not see the same kick, resulting in a transverse offset at the IP.

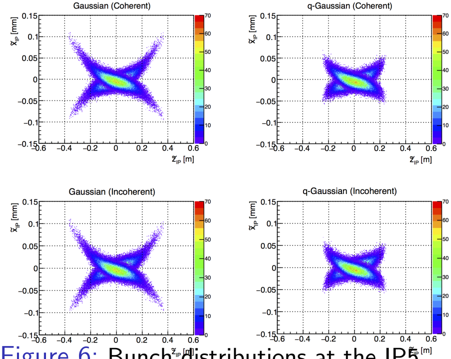


Figure 6: Bunch distributions at the IP5 with coherent ($\phi_1 = \phi_2$=100ps=0.25rad @ 400.79 MHz) and incoherent (ϕ_2=100ps and $\phi_1 = 0$) phase modulations.

Comparisons of peak luminosity

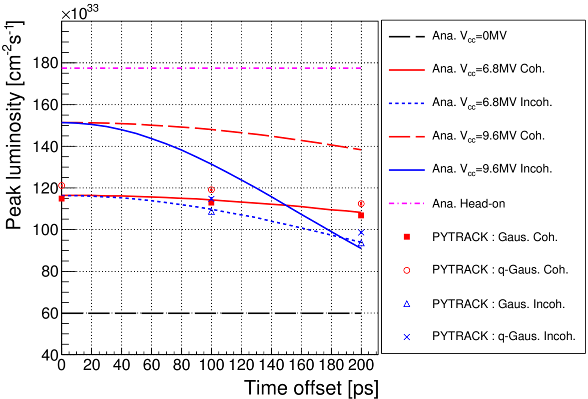


Figure 7: Peak luminosity with phase modulations in time. The peak luminosity is computed by numerical integration of Eq. 1 using Python.

- Coherent phase modulations at 100 ps: 2 % reduction (Analytical)
- Incoherent phase modulations at 100 ps: 6 % reduction (Analytical)

Summary

- Analytical model of peak luminosity with phase modulations has been derived. This study was presented at HL-LHC collaboration meeting in 2017 [6] and published at NIMA [3].
- Simulations have been applied with PYTRACK to compare to the analytical results, which is in good agreements.
- Reduction of peak luminosity is less than 2 % with the expected coherent phase modulation at 100 ps for both beams. In the limiting scenario of an incoherent phase modulation at 100 ps, it sums to 6 % of reductions.
- Phase modulations for the nominal HL-LHC operations are acceptable for physics runs.

Back Up

Luminosity calculation with phase modulations

$$L = \frac{\cos^2\frac{\theta}{2} N^2 f_{rev} n_b}{\pi^{5/2}\sigma^*_{x1}\sigma^*_{x2}\sigma_{z1}\sigma_{z2}\sqrt{8({\sigma^*_{y1}}^2+{\sigma^*_{y2}}^2)}} \int\int\int_{-\infty}^{\infty} e^{-\left(\frac{(\tilde{x}_{IP}\cos\frac{\theta}{2}-\tilde{z}_{IP}\sin\frac{\theta}{2})^2+\tilde{C}_1}{2{\sigma^*_{x1}}^2}+\frac{(\tilde{x}_{IP}\cos\frac{\theta}{2}+\tilde{z}_{IP}\sin\frac{\theta}{2})^2+\tilde{C}_2}{2{\sigma^*_{x2}}^2}\right)}\cdot$$

$$e^{-\left(\frac{(\tilde{x}_{IP}\sin\frac{\theta}{2}+\tilde{z}_{IP}\cos\frac{\theta}{2}-ct)^2}{2\sigma_{z1}^2}+\frac{(-\tilde{x}_{IP}\sin\frac{\theta}{2}+\tilde{z}_{IP}\cos\frac{\theta}{2}+ct)^2}{2\sigma_{z2}^2}\right)} d\tilde{x}_{IP}\ d\tilde{z}_{IP}\ d(ct).$$

where $\tilde{C}_1$ and $\tilde{C}_2$ are

$$\tilde{C}_1 = \Big(\beta^*\beta_{c.c}\frac{eV_1}{E_s}\sin\left(k\left(\tilde{x}_{IP}\sin\frac{\theta}{2}+\tilde{z}_{IP}\cos\frac{\theta}{2}-ct\right)+\phi_1\right)$$
$$+2\sqrt{\beta^*\beta_{c.c}}\left(\tilde{x}_{IP}\cos\frac{\theta}{2}-\tilde{z}_{IP}\sin\frac{\theta}{2}\right)\Big)\frac{eV_1}{E_s}\sin\left(k\left(\tilde{x}_{IP}\sin\frac{\theta}{2}+\tilde{z}_{IP}\cos\frac{\theta}{2}-ct\right)+\phi_1\right)$$

$$\tilde{C}_2 = \Big(\beta^*\beta_{c.c}\frac{eV_1}{E_s}\sin\left(k\left(-\tilde{x}_{IP}\sin\frac{\theta}{2}+\tilde{z}_{IP}\cos\frac{\theta}{2}+ct\right)-\phi_2\right)$$
$$-2\sqrt{\beta^*\beta_{c.c}}\left(\tilde{x}_{IP}\cos\frac{\theta}{2}+\tilde{z}_{IP}\sin\frac{\theta}{2}\right)\Big)\frac{eV_1}{E_s}\sin\left(k\left(-\tilde{x}_{IP}\sin\frac{\theta}{2}+\tilde{z}_{IP}\cos\frac{\theta}{2}+ct\right)-\phi_2\right)$$

q-Gaussian distribution

q-Gaussian distribution [4]:

$$F(J) = F_0 \left(1 - \frac{J}{J_0}\right)^n, \tag{2}$$

where the normalized coefficient F_0, the action $J = \epsilon/(2\pi)$ (longitudinal emittance ϵ) and the J_0 corresponds to the initial full longitudinal emittance (ϵ_0)

We define the bunch length as 4-σ which is equivalent to the full width at half maximum (FWHM)

For Further Reading

[1] R. Thomas and L. Medina,
"Parameter update for the nominal HL-LHC: Standard, BCMS, and 8b+4e",
HL-LHC parameters V6.1.0, 2017

[2] T. Mastoridis, P. Baudrenghien and J. Molendijk,
"Cavity voltage phase modulation to reduce the high-luminosity Large Hadron Collider rf power requirements"
PRST-AB, vol. 20, 2017.

[3] E. Yamakawa, R. Apsimon, P. Baudrenghien, R. Calaga, A.C. Dexter
"Luminosity reduction caused by phase modulations at the HL-LHC crab cavities"
NIM-A, vol. 908, 2018.

For Further Reading

[4] E. Metral, et at.,
"Update of the HL-LHC operational scenarios for proton operation",
CERN-ACC-NOTE-2018-0002, 2018.

[5] H. Timko, H. Muller, J.A. Lasheen, D. Quartullo,
"Benchmarking the beam longitudinal dynamics code BLonD",
IPAC'16, 2016.

[6] E.Yamakawa, P. Baudrenghien, R. Calaga, R. Apsimon and A. C. Dexter,
"Crab cavity studies including full detuning & offsets due to long range beam-beam interactions",
7th HL-LHC Collaboration Meeting, 2017.