BUNCH LENGTHS RESTRICTIONS AT LHC BY LONGITUDINAL COUPLED BUNCH INSTABILITIES

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Abstract

A future luminosity upgrade of the LHC may be based on strong focusing quadrupole magnets at the interaction regions. Due to the hourglass effect and the effects of the beam-beam interaction caused by the crossing angle, the bunch length could become an important quantity for the luminosity. Then, bunch lengths shorter than the nominal ones (0.31 m) are desirable.

This poster gives estimates for the minimum bunch lengths at which Landau Damping is lost for the three scenarios: without additional measures, applying RF amplitude modulation and the use of a higher harmonic RF system for bunch compression. Estimates for the minimum required RF kick strengths of a coupled bunch feedback system are also given.

Bunch length with completely preserved emittance (single RF)

The longitudinal emittance ε depends on the bunch length l as [3]

$$\varepsilon = \pi\, \Delta t\, \Delta E$$

With [4]

$$\Delta t = \frac{l}{2\,c}$$

$$\Delta E = \beta \sqrt{\frac{2\,E_s}{\eta}} \sqrt{\frac{e}{2\pi}\frac{V}{h}\left(1-\cos\left(\frac{\omega_{RF}\, l}{2\,c}\right)\right)}$$

where c is the speed of light, ΔE the energy deviation, Δt the time deviation of a particle with phase deviation $\Delta\varphi = \omega_{RF}\, l/2$, β = v/c, E_s the energy of the synchronous particle and $\eta = 0.0003225$ the slip factor. The RF parameters of LHC are a sum voltage of $V = 16$ MV and the frequency of $\omega_{RF} = 2\pi\ 400.8$ MHz resulting in the harmonic number $h = 35640$.

At the injection energy of E_s = 450 GeV the longitudinal (4σ) emittance will be ε = 1 eVs. It is increased during acceleration to ε = 2.5 eVs at top energy E_s = 7 TeV [1, 2] corresponding to a full bunch length of 0.31 m. With a completely preserved longitudinal emittance of ε = 1 eVs the bunch length would be:

$$l_{1\,\mathrm{eVs},\ 7\,\mathrm{TeV}} = 0.19\ \mathrm{m} \qquad \text{(single RF system)}$$

Minimum bunch length stabilized by Landau damping (single RF)

Following [5] the coherent frequency shift Δf_{imp}, caused by the effective impedance Z_L/n at a bunch intensity I_b, a bunch length l and nominal bunch spacing of 25 ns is at the LHC given by

$$\Delta f_{imp} = 0.0237\,\frac{\mathrm{Hz}}{\Omega}\left(\mathrm{Im}\,\frac{Z_L}{n}\right)\left(\frac{I_b}{10^{11}\,\mathrm{part.}}\right)\left(\frac{l}{\mathrm{m}}\right)^{-3}$$

Landau damping will suppress instabilities up to a threshold value of

$$\Delta f_{\mathrm{threshold,Landau}} = 6.45\ \mathrm{Hz}\left(\frac{l}{\mathrm{m}}\right)^{2}$$

By setting $\Delta f_{\mathrm{threshold,Landau}} = \Delta f_{imp}$ we can calculate the minimum bunch length at which Landau damping will be lost:

$$\frac{l_{\min}}{m} = \sqrt[5]{\frac{3.57\cdot 10^{-3}}{\Omega}\left(\mathrm{Im}\,\frac{Z_L}{n}\right)\left(\frac{I_b}{10^{11}\,\mathrm{part.}}\right)}$$

The following table shows the minimum bunch length for the most recent estimate of the longitudinal impedance of Im Z_L/n = 0.08 Ω [2] and an older estimate Im Z_L/n = 0.28 Ω [5] which may be viewed as a worst case value:

$l_{\min}$	Im Z_L/n = 0.08 Ω	0.28 Ω
$I_b = 1.1\ 10^{11}$ part.	0.20 m	0.26 m
$I_b = 1.7\ 10^{11}$ part.	0.22 m	0.28 m

For ultimate intensity $I_b = 1.7\cdot 10^{11}$ particles and also for nominal intensity $I_b = 1.1\cdot 10^{11}$ particles Landau damping will be lost because the values exceed the value of $l_{1\mathrm{eVs},7\,\mathrm{TeV}} = 0.19$ m.

Summary

With the given RF system, shorter bunches in the LHC are not feasible by switching off the controlled emittance blow up, used at standard operation. For the most recent estimate of the effective longitudinal impedance, a modulation of the RF amplitude may be sufficient to stabilize the beam in case one does not apply the controlled emittance blow up. This is no longer the case for smaller initial emittances or larger impedances. Larger impedances may be caused by operational constraints, as for example collimators for machine protection or for the reduction of back ground events in the high energy experiments. In such a case additional measures have to be taken.

One measure is a higher harmonic RF system for bunch compression. For the most recent estimate of the effective impedance the beam should be well stabilized by Landau damping. Investigations on the contribution of this RF system itself to the effective impedance are under way [9].

Alternatively one may set up a longitudinal coupled bunch feedback system. Then, the minimum bunch length depends on the initial emittance and the (noise) performance of the feedback system.

$l_{4\sigma}$	RF system	low Im Z_L/n	high Im Z_L/n
0.19 m	400 MHz	RF AM	0.21 m
0.16 m 0.12 m?	400 MHz +1.2 GHz	blow up —	blow up RF AM feedback?

A set up of fast multi bunch beam diagnostics and data logging, comparable to the system used at the HERA proton ring, may be required for the study of the instabilities and the supervision of the measures taken.

Stabilization by RF amplitude modulation (single RF)

The minimum bunch length at which Landau damping is lost, is not too far away from the theoretical bunch length value in the case of a single RF system. A method leading to a doubling of the instability threshold $\Delta f_{\mathrm{threshold}}$ may be sufficient to stabilize the beam. Such a method is the modulation of the RF amplitude. For the LHC it increases the instability threshold by about [6]

$$\Delta f_{\mathrm{threshold,AM}} = 0.51\ \mathrm{Hz}$$

resulting in

$$\Delta f_{\mathrm{threshold}} = \Delta f_{\mathrm{threshold,Landau}} + \Delta f_{\mathrm{threshold,AM}}$$

Setting again $\Delta f_{\mathrm{threshold}} = \Delta f_{imp}$ we can re-calculate the minimum bunch length at which Landau damping will be lost. The results are given in the following table:

$l_{\min}$	Im Z_L/n = 0.08 Ω	0.28 Ω
$I_b = 1.1\ 10^{11}$ part.	0.15 m	0.21 m
$I_b = 1.7\ 10^{11}$ part.	0.17 m	0.23 m

In the case LHC will have an effective longitudinal impedance of Im Z_L/n = 0.08 Ω the modulation of RF amplitude should be sufficient for stabilizing the beam and a shorter bunch length is obtained. The safety margins are comparable to the safety margins obtained at normal operation with controlled beam blow up.

But, in the case the initial emittance is smaller or the longitudinal impedance larger, additional measures have to be taken.

Longitudinal coupled bunch feedback

A coupled bunch feedback system has to damp instabilities faster than the beam blows up and the self-stabilizing by Landau damping takes place. The required kick voltage V_{FBK} of a longitudinal coupled bunch feedback depends on the maximum growth rate $\Delta f_{\mathrm{threshold,Landau}}/f_s$ stabilized by Landau damping, the RF voltage V_{RF} and the minimum detectable phase oscillation $\Delta\phi_{det}$ like [5]

$$V_{FBK} > 2\,V_{RF}\,\frac{\Delta f_{\mathrm{threshold,\,Landau}}}{f_s}\,\Delta\phi_{det}$$

For the LHC parameters and a minimum detectable phase oscillation of 0.2° [10, p. 32] this condition obeys

$V_{FBK} > 3$ kV for single RF system

$V_{FBK} > 60$ kV for double RF system.

These estimates does not take into account transient effects at injection or during acceleration. Fast damping of synchrotron oscillations caused by such effects may require larger kick strengths.

Higher harmonic RF system

A higher harmonic RF system with three times the frequency (1.2 GHz) [8] for bunch compression is under investigation [9]. With the resulting double RF system one usually injects into the buckets of the lower harmonic system, whereas the higher harmonic system is operated so, that its contribution to the sum voltage is 1/4 or less. During acceleration the voltage of the higher harmonic system is increased, such that it completely builds up the buckets at top energy.

The energy deviation ΔE is in the non-accelerating case given by

$$\Delta E = \beta\sqrt{\frac{2\,E_s}{\eta}}\left(\frac{e}{2\pi}\left(\frac{V_{400}}{h_{400}}\left(1-\cos\left(\frac{\omega_{RF}}{2\,c}\,l\right)\right) + \frac{V_{1200}}{3\,h_{400}}\left(1-\cos\left(\frac{3\,\omega_{RF}}{2\,c}\,l\right)\right)\right)\right)^{-1/2}$$

resulting with the voltages V_{400} = 16 MV and V_{1200}= 43 MV in the bunch length of

$$l_{1\mathrm{eVs},\,7\,\mathrm{TeV}} = 0.12\ \mathrm{m}$$

$$l_{1.8\,\mathrm{eVs},\,7\,\mathrm{TeV}} = 0.16\ \mathrm{m}$$

in the case of complete emittance preservation and in the case some (controlled) blow up will take place.

An approximation for the Landau damping in a double RF system is for $r_{12} < 1/h_{12}$ given by [10, p. 77]

$$\Delta f_{\mathrm{threshold,\ Landau}} = 19.4\ \mathrm{Hz}\,\frac{1+r_{12}\,h_{12}^{3}}{\sqrt{1+r_{12}\,h_{12}}}\left(\frac{3\,l}{\mathrm{m}}\right)^{2}$$

where $r_{12} = V_{400}/V_{1200}$ is the voltage ratio and $h_{12} = 1/3$ the ratio of the harmonic numbers. The value 19.4 Hz comes from increased synchrotron frequency due to the 1.2 GHz system. At top energy the condition $r_{12} < 1/h_{12}$ is fulfilled and we get

$$\Delta f_{\mathrm{threshold,\ Landau}} = 167\ \mathrm{Hz}\left(\frac{l}{\mathrm{m}}\right)^{2}$$

The following table shows the minimum bunch length at which Landau damping will be lost at the double RF system:

$l_{\min}$	Im Z_L/n = 0.08 Ω	0.28 Ω
$I_b = 1.1\ 10^{11}$ part.	0.08 m	0.11 m
$I_b = 1.7\ 10^{11}$ part.	0.09 m	0.12 m

In the case some controlled blow up is applied to increase the longitudinal emittance to ε = 1.8eVs, there should be sufficient Landau damping for an effective impedance of Im Z_L/n = 0.08 Ω. But, the higher harmonic RF system itself will contribute to the effective longitudinal impedance. The value for this contribution is under investigation [9].

References

[1] Home page of the LHC project, ‘Design Performance’, http://lhc-new-homepage.web.cern.ch, October 2004

[2] O. Brüning (ed.), P. Collier (ed.), P. Lebrun (ed.), S. Myers (ed.), R. Ostojic (ed.), J. Poole (ed.), P. Proudlock (ed.), ‘LHC design report vol.1 the LHC main ring’, CERN Report No. CERN-2004-003, p. 101, 2004

[3] D. A. Edwards, M. J. Syphers, An Introduction to the Physics of High Energy Accelerators (John Wiley & Sons, 1993)

[4] W. Pirkl, ‘Longitudinal Beam Dynamics’, in Proceedings of CERN Accelerator School - Fifth Advanced Accelerator Physics Course, Rhodes, Greece, 1993 (CERN Report No. CERN-95-06-vol.1, p. 233, 1995)

[5] D. Boussard, D. Brandt and L. Vos, ‘Is a longitudinal feedback system required for LHC’, LHC Project Note 205 (November 1999)

[6] E. Vogel, T. Bohl, U. Wehrle, ‘RF Amplitude Modulation to Suppress Longitudinal Coupled Bunch Instabilities in the SPS’, presented at: ninth European Particle Accelerator Conference EPAC 2004 , Lucerne, Switzerland 2004 (CERN Report No. CERN-AB-2004-077, 2004)

[7] E. Vogel, ‘Status of the Longitudinal Emittance Preservation at the HERA Proton Ring in Spring 2003’, DESY Report No. DESY-HERA-03-03 (2003)

[8] O. Bruning, R. Cappi, R. Garoby, O. Grobner, W. Herr, T. Linnecar, R. Ostojic, K. Potter , L. Rossi, F. Ruggiero (editor), K. Schindl, G. Stevenson, L. Tavian, T. Taylor, E. Tsesmelis , E. Weisse, F. Zimmermann, ‘LHC Luminosity and Energy Upgrade: A Feasibility Study’, LHC Project Report 626, December 2002

[9] J. Tückmantel, personal communication, CERN October 2004

[10] E. Vogel, ‘Fast Longitudinal Diagnostics for the HERA proton Ring’, DESY Report No. DESY-THESIS-2002-010, 2002