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Large Hadron Collider Project **LHC Project Report 1097**

RF WIRE COMPENSATOR OF LONG-RANGE BEAM-BEAM EFFECTS

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Abstract

The dynamic aperture of the proton beam circulating in the Large Hadron Collider (LHC) is expected to be limited by up to 120 long-range beam-beam encounters. In order to perfectly compensate the LHC long-range beambeam effect for nominal as well as for so-called ‘PACMAN’ bunches, i.e. bunches at the start or end of a bunch train, the strength of a wire compensator should be adjusted for each bunch individually.

Here an RF-based compensator is proposed as a practical solution for the PACMAN compensation. We show that this approach also allows relaxing the power and precision requirements compared with those of a pulsed DC device, to a level within the state-of-the-art of RF technology. Furthermore it permits the use of a passive circulator in the tunnel close to the beam and thus a significant reduction of the transmission line length and of the associated multiple reflections. Simulations of dynamic aperture and emittance growth, issues related to RF phase noise, and first experimental results from laboratory models are presented.

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The dynamic aperture of the proton beam circulating in the Large Hadron Collider (LHC) is expected to be limited by up to 120 long-range beam-beam encounters. In order to perfectly compensate the LHC long-range beam-beam effect for nominal as well as for so-called ‘PACMAN’ bunches, i.e. bunches at the start or end of a bunch train, the strength of a wire compensator should be adjusted for each bunch individually.

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INTRODUCTION

The long-range beam-beam interaction (LRBBI) next to the two high-luminosity interaction points (IPs) will ultimatively limit the performance of the LHC. Wire compensators suitably located and powered can overcome this limitation [1]. Due to the bunch-filling pattern of the LHC almost half of the bunches are so called PACMAN bunches, which are located at the start or end of the bunch train and, therefore, experience a reduced number of LRBBIs on one side of each main IP. Fig. 1 shows the simulated [2] achievable gain in dynamic aperture (DA) as a function of the compensator current for a nominal bunch and for an extreme PACMAN bunch (no long-range collisions at allon one side of the IP). While already an intermediate DC-current can improve the dynamic aperture for both, a pulsed BBLR could be adjusted to optimise the performance of each bunch individually. The resulting current ramp needs to reach a typical BBLR current value of 100 Am within 0.4 μs.

Any amplitude jitter on the BBLR causes emittance growth, whose quantitative value crucially depends on the jitter frequency spectrum. In the simulations a worst-case scenario of white Gaussian noise was assumed. The noise can originate either from the power generator, from beam-induced signals or from transmission line effects (due to radiation issues the power generator cannot be placed right next to the BBLRs, but must be connected by a transmission line where multiple reflections enhance the noise).

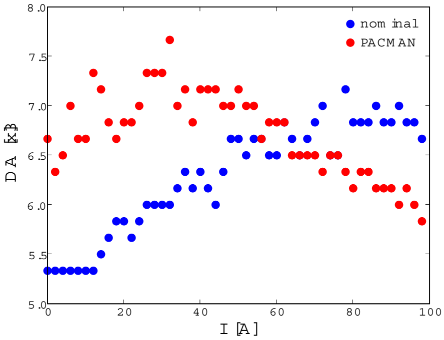
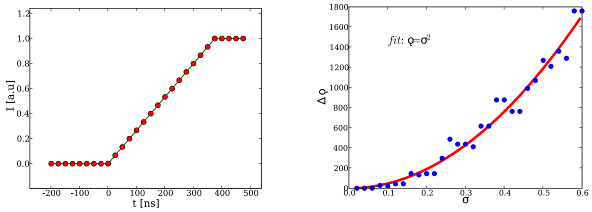


Figure 1: Dynamic aperture (DA) in the nominal LHC as a function of the compensator current for a nominal bunch and an extreme PACMAN bunch. While an intermediate DC-current level can improve both, a pulsed device could increase the performance even further.

PROBLEMS OF PULSED DC BBLR

The first intuitive operational sketch of such a pulsed device is illustrated in Fig. 2 a). The dots indicate the time instances when a bunch passes the BBLR and a certain current value is required. In a “pulsed DC” BBLR two current value data points are connected by a linear ramp. At the required pulsing frequencies the BBLR resembles an inductor, whose characteristic equation $U = L \times \dot{I}$ is used to create the current ramp using an appropriate driving voltage. The bottle neck of this implementation are noise issues as any timing error gets transferred linearly into an amplitude noise error. BBTrack [2] was used to simulate the effect of noise. Fig. 2 b) shows the expected quadratic dependence of the emittance growth on the jitter amplitude. Allowing for 10% emittance growth in 20h the timing jitter must be less than $\Delta t < 0.02$ ns. It turned out that this is beyond the scope of today’s high-current switching devices.



(a) A “pulsed DC” BBLR connects two time-current data-points by a straight line.

(b) Emittance growth as a function of the noise amplitude for the “pulsed DC” BBLR.

Figure 2: Principle and noise study of a “pulsed DC” BBLR.

RF-BBLR

Principle

An RF-based pulsed BBLR turned out to be a better and technologically feasible solution. As shown in Fig. 3 the “RF-BBLR” current follows an amplitude modulated 40 MHz sine wave (matching the 25ns bunch spacing). In this case the BBLR length is no longer a free design parameter, but it is chosen to represent a $\lambda/4$ resonator at 40 MHz (Fig. 4). The current slope and the power requirements are now functions of the coupling from the signal generator to the resonator.

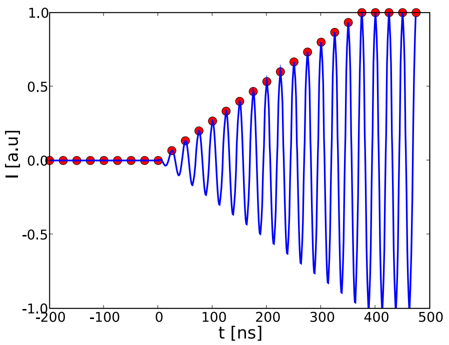


Figure 3: The current of an RF-BBLR follows an amplitude modulated 40 MHz sine wave.

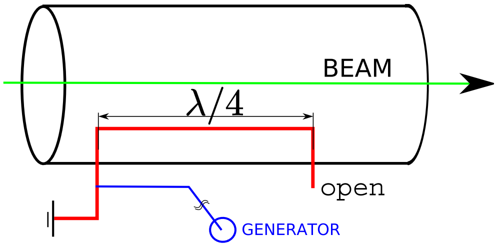


Figure 4: The RF-BBLR is based on a resonating structure. The wire length is no longer a free design parameter, but represents a $\lambda/4$ resonator at 40 MHz.

Advantages

- As it operates as a resonator, the RF-BBLR requires less input power to reach an equivalent strength. Conservatively one can estimate the quality factor Q to be 10, which results in the same factor of reduction in power required from the generator.
- As the electromagnetic field in the RF-BBLR counterpropagates to the beam (Fig. 5), the beam samples a magnetic and an electric field. This reduces the required current by a factor of 2 and therefore the required power by a factor of 4, compared with a “pulsed DC” BBLR.
- As an RF-BBLR is based on a resonating structure (Fig. 4) it is very stable in time and operates as reliable as an accelerating RF-cavity
- The RF-BBLR allows the use of a passive circulator in the tunnel close to the beam which dumps reflected waves and keeps them from propagating back into the generator.
- As the derivative of the BBLR-current vanishes at the moment of the bunch passage, the effect of timing jitter is significantly reduced. The modified amplitude-timing correlation causes a non-quadratic emittance-growth function (Fig. 6; to be compared with Fig. 2b). The sinusoidal current function results in a reduced timing noise sensitivity.
- Choosing the amplitude modulation suitably, almost any current ramp can be generated (even faster than the natural slope)

All in all, this approach allows us to relax the power and precision requirements to a level well within the state-of-the-art of today’s RF technology.

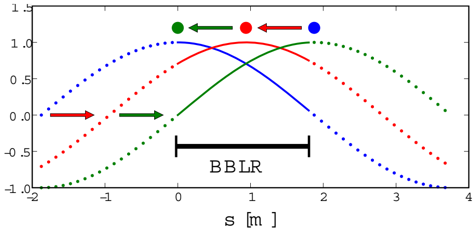


Figure 5: As the resonating waves on the BBLR counterpropagate to the beam, both the magnetic and the electric field take contribute to the net force, while the transit-time effect reduces the impact of fringe fields.

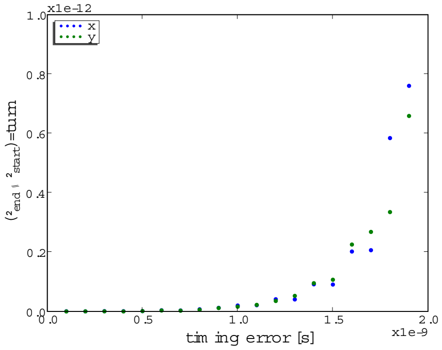


Figure 6: As the derivative of the BBLR-current vanishes at the moment of the bunch passage, the tolerance on the timing stability is much relaxed.

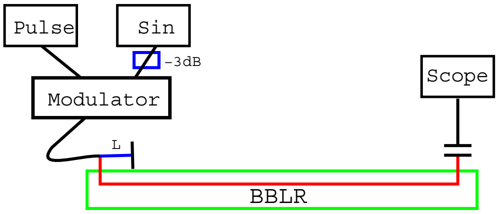


Figure 7: Measurement setup for the RF-BBLR prototype.

First Prototype

In order to test this novel scheme a prototype was constructed and tested. The BBLR was fed with an amplitude modulated 40 MHz signal via a connection network with varying coupling strength. The current on the BBLR was measured capacitively (Fig. 7).

Fig. 8 shows the experimentally measured current ramp, which exhibits the desired shape but with a ramp rate still needing adjustment.

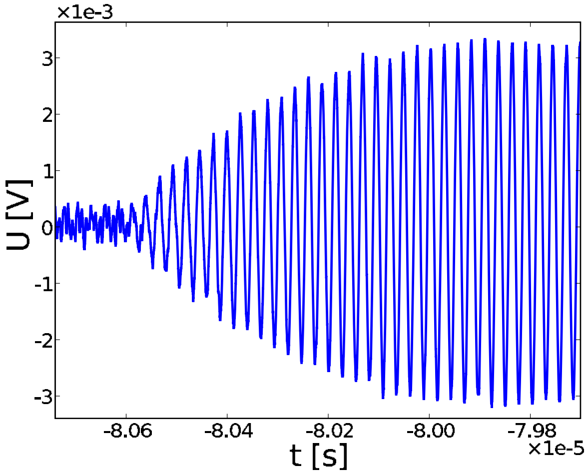


Figure 8: Measured excitation of a critically coupled RF-BBLR prototype. The coupling still needs to be further adjusted to reach the desired ramp rate.

For an RF excitation with a step like envelope we obtain depending on the coupling of the resonator responses shown in Fig. 9, which show the typical exponential shape. Obviously the coupling of the BBLR is fixed and will be adjusted once during installation. Thus in order to control in operating the amplitude and phase over the batch one should apply the classical gain and phase loop circuits [3]. With such external circuits one can implement a linear rising voltage slope with constant phase (Fig. 10) and adjustable risetime.

CONCLUSION

The RF-BBLR promises to be a viable tool for individually adjusted long-range beam-beam wire compensation. This approach allows relaxing the power and precision requirements to a level well within the state-of-the-art of today's RF technology.

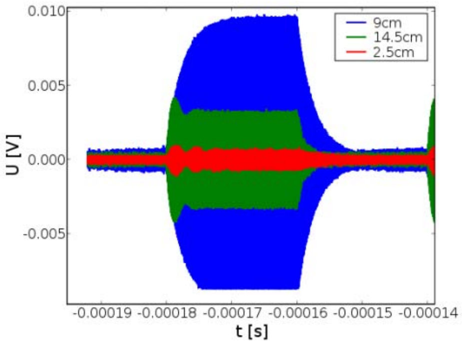


Figure 9: Measurements of RF-BBLR signal for three different coupling strengths, implemented by altering the resonator length via a set of extension pieces. The varying coupling strength results in different ramp rates and in a change of the overall resonator gain.

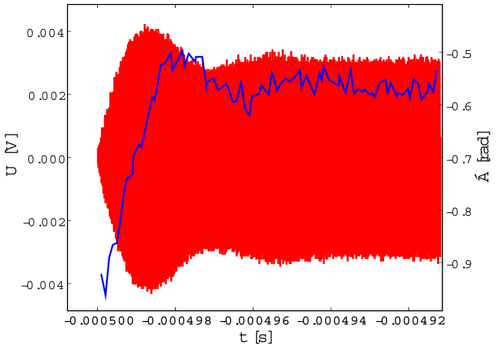


Figure 10: The changing phase relation between the incoming and resonating signal must be corrected in order to be constant during the ramp.

REFERENCES

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[3] W. Hoefle, "Do the septum cavities for the LHC longitudinal damper require a tuner ?", SL-Note-96-04-RF, 1996